ABSTRACT

ULTRACAPACITORS FOR OFF- GRID WIND POWER STORAGE SYSTEMS

By

Hans Tanis

The main reason for wind turbine to be not as prevalent as traditional power systems is because they do not have an effective storage capacity. However, researchers in material science and engineering have found ways to resolve this problem by developing “ultracapacitors” that store energy by assembling ions at the surface of a porous material. That is why ultracapacitors coupled with the energy storage battery could present a challenge to the electrical power grid. Such a design allows ultracapacitors to charge in matter of minutes and not hours. This innovation would create a significant impact on electronic items such as computers, smartphones and tablets. In addition, it would revolutionize the electric car industry, solar and wind power industries that are looking for a quick way of storing energy. Such an invention would be ideal for off-grid systems and wind power that rely on sun and wind that are not consistent in nature. In fact, ultracapacitors would allow the solar off-grid to store energy during the day and use it whenever required. The same process can be applied for wind energy systems that can store the energy when the wind is active. The field of ultracapacitors is widening due to a variety of approaches that have been used to deliver the best possible use for this product.

The objective, in this thesis, is to analyze the effective use of ultracapacitors coupled with wind turbine in the market. This analysis addresses efficiency, cost, reliability, portability and durability in order to challenge the status quo of the energy

provider in the market. This study will also investigate the design that would be the most promising in providing the best challenge to the future of storage energy systems.

ULTRACAPACITORS FOR OFF GRID WIND POWER SYSTEMS

By

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LIST OF ABBREVIATIONS

WECS	Wind Energy Conversion System
Ucaps	Ultracapacitors
ESS	Energy Storage System
EDLC	Electrochemical Double Layer Capacitor
EV	Electrical Vehicle
C	Capacitor
Q	Charge
ESR	Error Series Resistance
LTO	Lithium Titanium Oxide (Li_4 Ti_5 O_{12})
SOC	State of Charge
DC	Direct Current
IGBT	Insulated- Gate Bipolar Transistor
PWM	Pulse Width Modulation
MHV	Micro-hybrid Vehicle
AGM	Absorbent Glass Mat
SLI	Starting Light Ignition
OEM	Original Equipment Manufacturer

CHAPTER 1

INTRODUCTION

1.1 Overview of Ultracapacitors

In recent years, ultracapacitors have become the supplemental source of storage energy to the improved or advanced battery design. Capacitors have been around for many years and made a great impact on being passive components in micro circuitry. However, the role of these capacitors starts to regress when it comes to using them on units that require a continuous energy source over a lengthy period of time. This is when ultracapacitors have become known for their storage capacity but could not hold charges for a great length of time. In fact, scientists, through their research, have come up with materials that could improve their capacity in order to achieve such goals. Materials such as lithium ions, carbon nanotubes, graphene and cyanide solvent as electrolyte provide them the tools to begin building an ultracapacitor that can bring them closer to the goal of having a product that could become the alternative to fossil fuel when coupled with an effective battery backup system [4].

Ultracapacitors have shown significant results when they are used as complement to regular batteries. They are able to protect the battery cell from being damaged against sudden power surge that can happen unexpectedly. The role of these components has been evolving over the years due to the constant demand for alternative sources of energy [4]. The road to success is not too far because a number of scientists have come up with some promising designs that could yield results as the years go by.

CHAPTER 2

Traditional Capacitor

2.1 Capacitor technology

A capacitor is a device made up of two parallel plates in which the electric charge is stored in the space between the plates. The capacitance is the ability for a capacitor to hold electric charge, which is based on the ratio of the charge to the potential difference:

$$C = Q / \Delta V \qquad (1.1)$$

The area of the capacitor plates is directly proportional to C while inversely proportional to the distance between them. When the area of the plates is doubled, the capacitance is doubled, and the capacitance is halved if the distance between the plates is doubled [1]. The Farad is the unit for capacitance and is also equal to one Coulomb per Volt. Generally, capacitors have small capacitances; that is why their values are always in micro Farads where $1\ \mu F = 10^{-6}$ F. The major task of a capacitor is to store energy, which is realized by the movement of a small amount of negative charge from the positive plate to the negative plate of a capacitor [1].

2.1.1 Energy Storage in Capacitor

Capacitors are made to store electrical energy. The work done to charge the capacitor is the amount of energy the device can handle. As the charging process is taking place, there is movement of charges from one plate to the other.

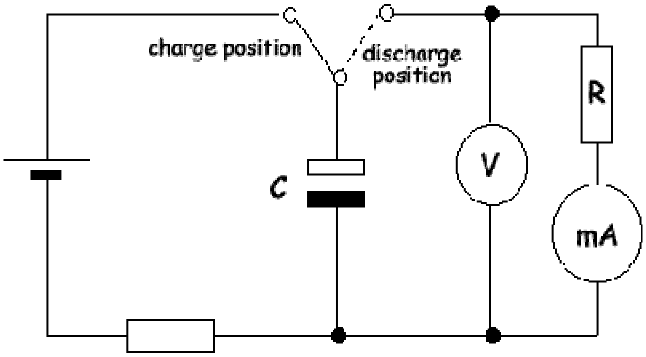

Figure 2.1 Charging and discharging of a capacitor [11].

This is analogous to a bucket filled up with charges +dq and being carried up a stair to be dumped at the top plate, thus, charging that plate with positive +dq. While this is occurring, the bottom plate is now charged negatively into –dq. As this process is going on over and over, this capacitor is partially charged and starts to generate an electric field that is not present at the beginning. At this point, there is a potential difference between the plates which is $\Delta V = Q/ C$. To add more charges to the top plate, the electrical repulsion driven by those charges will require a certain amount of work: $dW = \Delta V.dq$ [12].

However, when full capacity is reached and the total amount of work done is:

$$W=1/2 \times Q^2/C \qquad (1.\ 2)$$

$$U = ½\ C\ V^2 = Q^2 / 2\ C = ½\ Q\ V \qquad (1.\ 3)$$

2.1.2 Series and Parallel Capacitors

Capacitors can be arranged in series or in parallel. Capacitors in series act like resistors in parallel while capacitors in parallel perform like series resistors. The rule for adding capacitance is the reverse of adding resistance:

For two capacitors in series:

The potential difference across the series capacitors is equal to the sum of the potential differences across the individual capacitors. These two capacitors can be substituted by equivalent capacitor $C_{eq} = Q / |\Delta V|$.

$$Q / C_{eq} = Q / C_1 + Q / C_2 \tag{1. 4}$$

$$1/ C_{eq} = 1/ C_1 + 1/ C_2 \tag{1. 5}$$

For two capacitors in parallel:

C_1 and C_2 are connected on the left side of the plate to the positive terminal of the battery and have the same electric potential as the positive terminal. The same connection also occurs to the right plates that are negatively charged and have the same potential as the negative terminal. The potential difference $|\Delta V|$ is the same across each capacitor [7].

$$C_{EQ} = C_1 + C_2 \tag{1. 6}$$

2.1.3 Dielectrics

One of the major components of a capacitor that make it hold charges is the dielectric. This is a material that is used to keep the plates of a capacitor apart which in turn increases the capacitance. Such capacitance reaches a higher value due to the dielectric constant ε. ε represents the measure of the dielectric strength. In addition, there are two types of dielectrics - a polar and a non-polar dielectric [12]. Figures 2.2 (a) and 2.2 (b), below, illustrate the difference between the two.

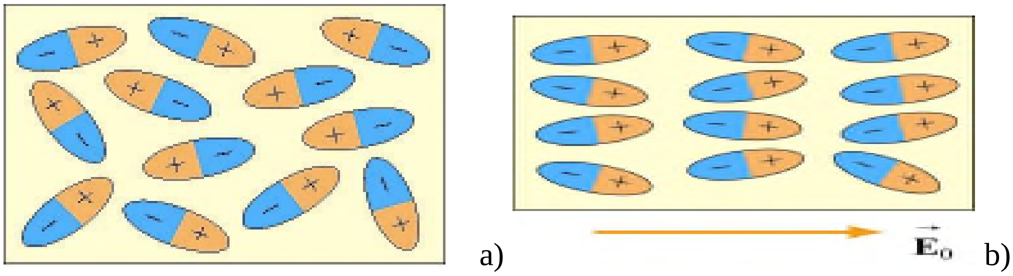

Figure 2.2 Orientations of polar molecules when (a) E_0 = 0 and (b) E_0 =/= 0 [12].

When there is no electric field present, (a) the polar molecules act at random; however, the response is different during an active electric field (b). Besides that, fields end up generating a field opposite to the aligned field but with a lesser magnitude. A non-polar dielectric has to be placed in an active field in order to be induced. Figure 2.3 shows the

Table 2.1. Dielectric properties of various materials

Material	ε	Dielectric strength (10^6 V/ m)
Air	1.00059	3
Paper	3.7	16
Glass	4−6	9
Water	80	

orientation of non-polar molecules.

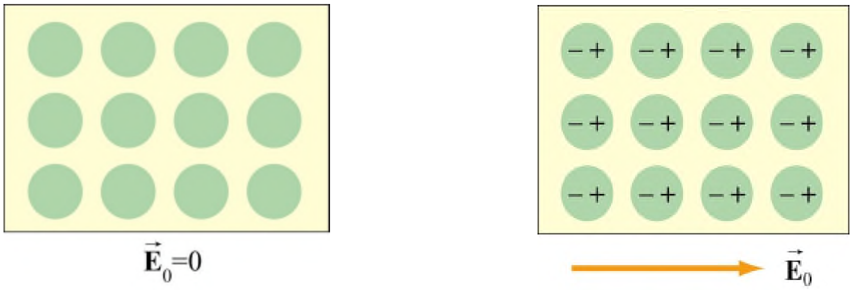

Figure 2.3 Orientations of non-polar molecules when (a) E_0 = 0 and (b) E_0 =/= 0 [12].

Due to the interaction of the charges between the plates, an electric field is observed. This field polarizes the molecules in the dielectric that leads to the positive electrons to move to the end of the plate that is connected to the positive side of the energy source while the negative electrons gravitate to negative side of that source [2]. The movement of electrons generates a row of negative charge by the positive plate and a row of positive charge by the negative plate.

Such separation of charge leads to an electric field in the dielectric that travels in the direction opposite to the original field of the capacitor.

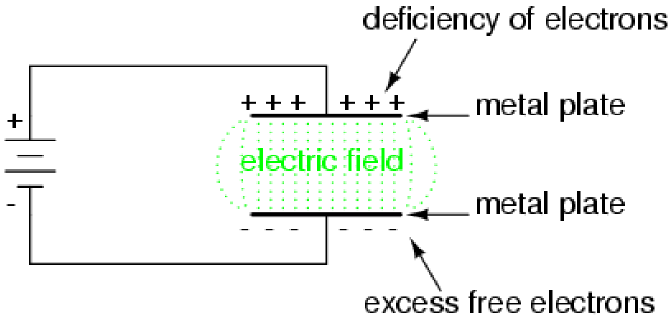

Figure 2.4 Electric field in a capacitor [7].

$$E_{net} = E_{free} - E_{induced} = E / \varepsilon \tag{1.8}$$

where ε is the dielectric constant and is always greater than zero [3-4]. This dielectric constant changes based on the material that one uses for the dielectric.

For a parallel-plate capacitor, the reduction in E means that ΔV is also reduced by a factor of ε [2]. Then, since C = Q / ΔV, we find that: $C_{new} = \varepsilon C_{old}$

If the potential difference across the capacitor is too large, then the electric field will be so strong that the electrons escape from their atoms and move toward the positive plate. This process causes the dielectric to breakdown by not just only discharging the capacitor, but also burns a hole in the dielectric and ruins the capacitor.

A narrower separation between conductors leads to a greater capacitance; such occurrence could also happen when the conductors have a larger surface area. In practice, breakdown voltage is when the dielectric between the plates releases a small amount of leakage current and also has limited electric field strength.

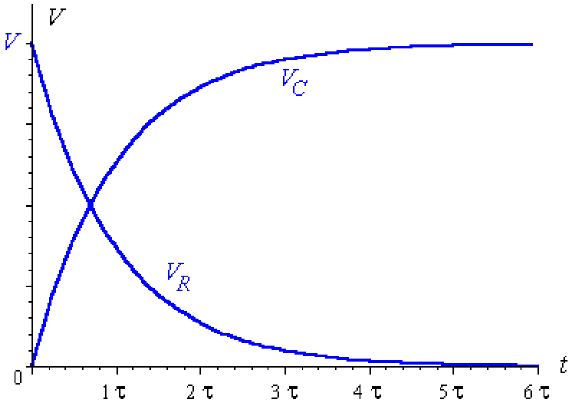

Figure 2.5 Plot of capacitance voltage versus capacitance resistance [14].

Capacitors are widely utilized to stop current from damaging electronic circuits while allowing alternating current to pass. They play a major role in softening the output of power supplies in analog circuits. In resonance circuits, they adjust radios to particular frequencies while in electric power transmission systems, they smooth the output of voltage and power flow [11].

2.1.4 Gauss's Law for Dielectrics

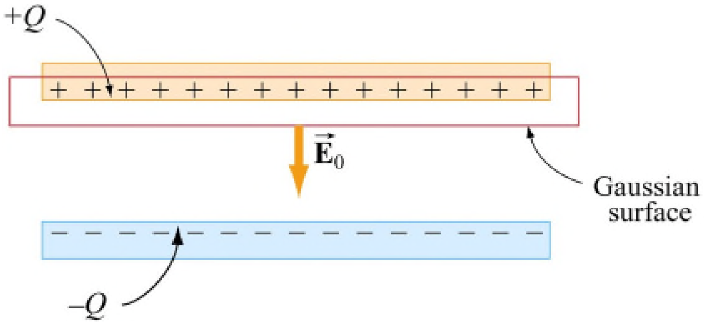

Figure 2.7 Gaussian surface in the absence of a dielectric [12].

Without an electric field, Gauss came up with an equation that satisfies the condition [11],

$$\int E.\, dA = E_0\, A = Q/\varepsilon_0 \quad , \Rightarrow E_0 = \sigma/\varepsilon_0 \qquad (1.9)$$

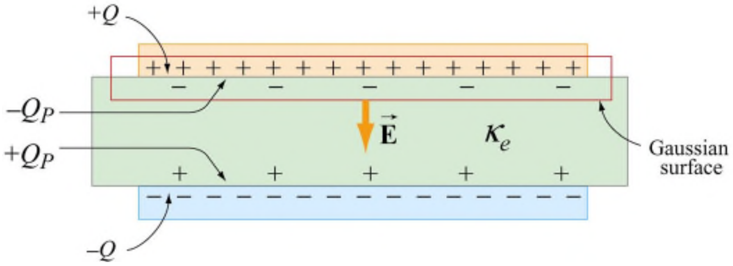

Figure 2.8 Gaussian surface in the presence of a dielectric [12].

However, with an active electric field, there is an induced charge Q_p generated and the net charge by Gaussian surface is $Q - Q_p$.

$$\int E.\, dA = EA = Q - Q_p / \varepsilon_0 A \qquad (1.\ 10)$$

$$E = Q - Q_p / \varepsilon_0 A \qquad (1.\ 11)$$

2.1.5 Dielectrics without Batteries

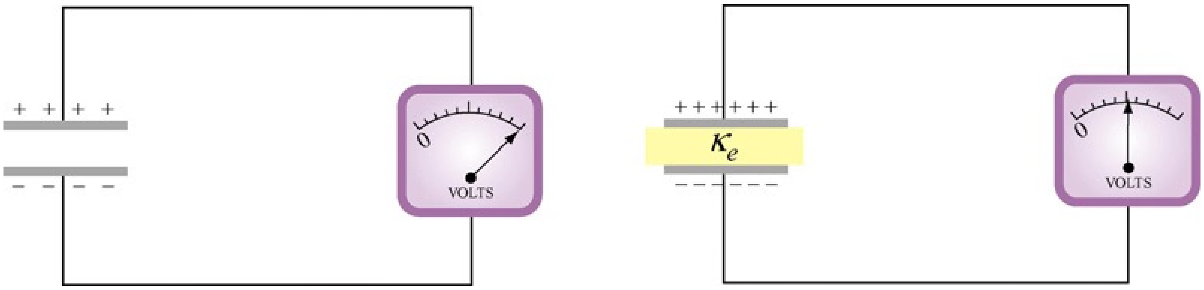

Figure 2.9 Inserting a dielectric material between the capacitor plates while keeping the charge Q_0 constant [12].

There is a potential difference of $| \Delta V_0 |$ across the battery terminals that is connected to a capacitor C_0 . This generates a charge $Q_0 = C_0 \, | \Delta V_0 |$ where, Q_0 = constant [4]. When a dielectric is placed between the capacitor plates, the potential difference increases by a factor, ε. Then, the capacitance value is:

$$C = Q / | \Delta V | = Q_0 / | \Delta V_0 | / \varepsilon = \varepsilon \; Q_0 / | \Delta V_0 | = \varepsilon C_0 \qquad (1.12)$$

2.1.6 Dielectric with Batteries

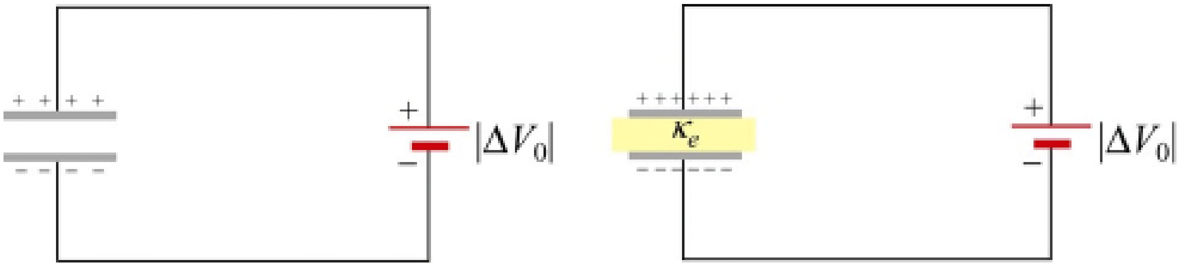

Figure 2.10 Dielectric materials between the plates while keeping a potential difference $|\Delta V_0|$ [12].

As shown above in Figure 2.10, the potential difference $|\Delta V_0|$ is maintained in order to maintain the plate charge by a factor ε:

$$Q = \varepsilon\ Q_0 \tag{1.13}$$

This charge Q_0 represents the charge on the plates without the dielectric present. The capacitance related to this condition is given by the equation:

$$C = Q / |\Delta V_0| = \varepsilon\ Q_0 / |\Delta V_0| = \varepsilon\ C_0. \tag{1.14}$$

Capacitors are manufactured in different shapes and sizes and play an important role in the electronic circuit system. They are used for a variety of purposes such as storing electric potential energy. When they are coupled with resistors, they slow down the change in voltages, to filter out unwanted frequency signals and creating resonant circuits. As the technology is constantly evolving, capacitors have also evolved into supercapacitors that have a different structure to support circuit systems that require quick power surge to be delivered to their load.

CHAPTER 3

ULTRACAPACITOR TECHNOLOGY

3.1 Overview of Ultracapacitor Design

3.1.1 Ultracapacitor Classification

The demand for an alternative way to store energy has led scientists to come up with the ultracapacitor design. The purpose of this device is to have the ability to charge and discharge electrical energy as the need occurs during the rise and fall of voltage to a load. The configuration of this component is similar to its counterpart, the capacitor. However, the ultracapacitor, formerly known as electric double-layer capacitor (EDLC), stores more energy (10 to 100 times) per unit volume than its electrolytic capacitors; besides, it allows more charge and discharge than conventional batteries. Supercapacitors use higher surface area and thinner dielectric to attain their higher capacitance, which in turn leads to higher energy density and power density. Such attribute allows them to rival batteries in energy storage systems and become an attractive solution when it comes to energy storage for an increasing number of applications. Supercapacitors are classified in three different classes: electrochemical double-layer capacitors, pseudocapacitors, and hybrid capacitors. Each class is grouped based on their characteristics that align with their unique way of energy storage [20]. The processes are called Faradaic, non-Faradaic and the mixture of the two. Faradaic deals with the transfer of charge between electrode and electrolyte while non-Faradaic does not involve any chemical structure; but charges are distributed on surfaces by physical means that do not use chemical bonds.

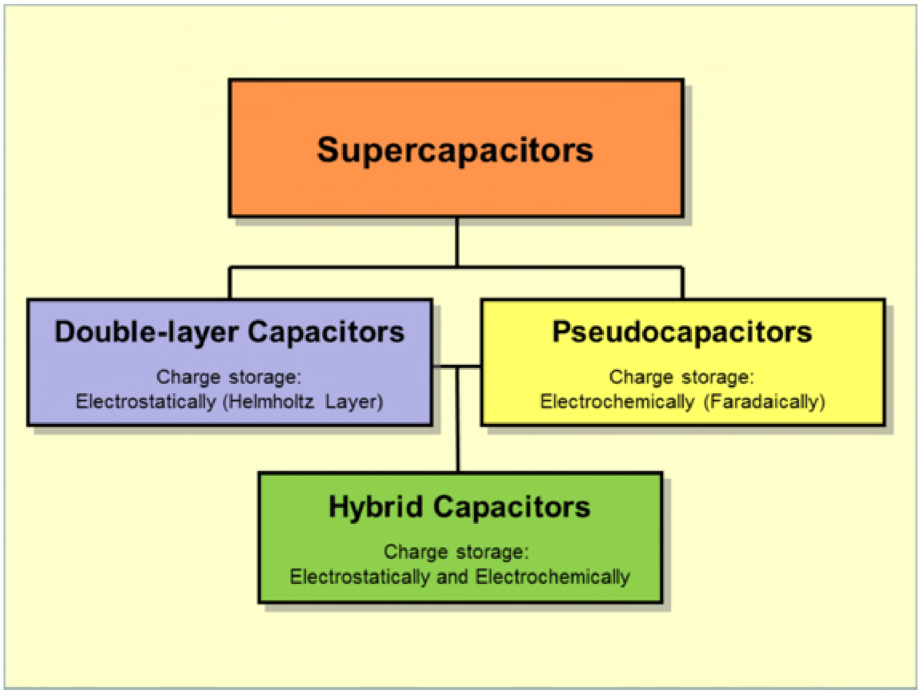

Figure 3.1 Classifications of Supercapacitors [19].

3.1.2 Electrochemical Double-Layer Capacitors

Electrochemical Double-Layer Capacitors (EDLC) are made of two carbon based electrodes, and electrolyte and a separator. As a non-Faradaic, EDLC utilizes an electrochemical double-layer of charge to store energy. Charges build up on the electrode surface when there is an applied voltage. Then ions in the electrolyte solution are spread across the separator in order to reach the electrode of the opposite charges. High charge density achievement in EDLC is based on these layers coupled with an increase in surface area and a decrease in distance between the electrodes. Due to the fact that there is no transfer of charge between electrolyte and electrode, there are no chemical changes that occur in the process. This is why EDLCs have high cycling stability.

EDLC can use an aqueous or organic electrolyte [9]. Such decision must be based on the purpose of the ultracapacitors because aqueous electrolytes have low equivalent series resistance (ESR) and low minimum pore size compared to organic electrolytes. But, aqueous electrolytes have a positive side that shows its low breakdown voltages. These tradeoffs give the opportunity to choose which ones are feasible for a specific application regarding ultracapacitors. Electrolyte plays an important role in the structural design of ultracapacitors. However, there are other classes of EDLCs that use different types of carbons to build up charge in their electrodes. These carbon materials are activated carbons, carbon aerogels, and carbon nanotubes.

Table 3.2 Electrochemical Double Layer Capacitors: Supercapacitors 2014-2024

	Aqueous	Non-aqueous organic
Voltage per cell	Low value enables the building of products for 0.7, 1.4, 2.1, 2.8, 3.5 Volts and up, with greater voltage flexibility (compared to increments of 2.3 or 2.7 Volts of organic based supercapacitors)	Maximum = 2.7V, with limited range flexibility
Manufacture	Simple	Difficult. Water sensitive and require dry conditions during production (trace quantities of water in the electrolyte can degrade the performance).
Cost	Low potential price	Higher price

Balancing circuit	Usually not required	Required
Time to reach leakage current stabilization	Less than 12 hours (for small capacitors in less than one hour)	72 hours – poor
Leakage current	Quick stabilization	Lengthy stabilization required. Balancing Circuit adds additional leakage current, which may be higher than the SC itself.
Energy density	Claimed to match lead acid batteries in some cases, with potential to match lithium-ion.	Not as good
Power density	Excellent. Higher ion mobility with higher conductance, which leads to faster charge/discharge.	Not as good but still excellent compared to batteries
Balancing resistor	No balancing resistor requirement, which decreases leakage current	Yes
Environmentally friendly	Green product	Not a green product. Acetonitrile typically used, which is harmful and flammable

3.1.3 Activated Carbons

Activated carbons are mostly used in the industry due to low cost, high surface area, and complex porous size. Even though capacitance is directly proportional to surface area, sometimes the electrode ions cannot fit the microspores because they are too big [9]. Such condition leads to a reduction of the capacitance level which in turn affects the storage capacity of EDLC.

3.1.4 Carbon Aerogels

Carbon aerogels has the ability to reduce Equivalent Series Resistance (ESR) that enhances higher power in supercapacitors. This can be achieved by bonding chemically to current collector. Carbon aerogel consists of a continuous link of carbon nanoparticles that spread into mesopores.

3.1.5 Carbon Nanotubes

Carbon nanotubes are used as an EDLC electrode material to achieve greater capacitance than activated carbons because of the structure of carbon nanotubes that allow it to provide a continuous distribution of charge. The mesopores in this material is intermeshed which give it the vast surface area compared to other carbon materials. Electrolyte ions can travel at ease in the mesoporous network that yields carbon nanotubes with low ESR, which leads to higher power density [9].

Table 3.2 Electrochemical Double Layer Capacitors: Supercapacitors 2014-2024

Market sector	Function – replacing, protecting or enhancing batteries or capacitors	Examples of actual and envisaged applications

Electronic – small devices	Replacing battery	Smart meters (AMR)
		GSM/GPRS transmitters
		Solid State Drive SSD i.e. solid-state disk or electronic disk, a data storage device that uses integrated circuit assemblies as memory to store data persistently
		USB powered audio systems
		Memory back-up
		M2M wireless communication such as Wireless Sensor Networks WSN – buffering energy harvesting
	Replacing capacitor	Increasing mobile phone camera flash reach ten times
		Mobile phone clock back-up
Electrical engineering – large equipment such as vehicles and wind turbines	Replacing battery	Replacing up to three battery packs in a truck to improve cold start and endurance in hotel operation when parked, extending battery life
		Opening vehicle doors in emergency
		Buffering energy harvesting
		Feathering wind turbine blades during power outage

	Protecting and enhancing battery	Across traction batteries to protect against fast charge and discharge and deep discharge and provide extra power when needed and longer battery life. Buffering wind turbine, solar and other energy harvested power

3.1.6 Pseudocapacitors

Pseudocapacitors use the Faradaic process that allows the transfer of charge between electrode and electrolyte. These processes can be achieved through electro sorption, reduction-oxidation reactions, and inter-processes. Conducting polymer and metal oxides are the materials used as electrodes in order to give Pseudocapacitors the structure needed to reach a significant capacitance and energy density [10].

3.1.7 Conducting Polymers

In conducting polymers, these materials provide a sizable capacitance and conductivity besides a low ESR. The greatest potential energy and power energy can be accomplished when the n/p type configuration reach the conducting polymer electrode. But, when the n type is not efficient, such condition impacts the potential of the supercapacitors. In addition, instability can be caused by mechanical stress on polymer during reduction-oxidation reactions.

3.1.8 Metal Oxides

Ruthenium oxide has been the centerpiece of a possible electrode for Pseudocapacitors because of its high conductivity and low ESR. When mixed with water, the capacitance exceeds that of carbon and polymer materials. However, the main hindrance is the cost factor, which researchers are working on in order to enjoy the benefit of this material.

3.1.9 Hybrid Capacitors

Hybrid capacitors use electrodes that can show either electrostatic or electrochemical capacitance due to their Faradaic and non-Faradaic processes. With such flexibility, hybrid capacitors reach greater power and energy density than other EDLCs without losing their cycling stability and affordability [10]. There are different types of hybrid capacitors: composite, asymmetric and battery-type.

3.1.10 Composite

Composites electrodes are able to reach higher capacitance because they are built from materials such carbon nanotubes, and polypyrrole. This is achieved under the structure of entangled mat, which provides a uniform mesh of polypyrrole and a three dimensional structure. This design leads to reduction in the mechanical stress that is related to insertion or removal of ions in the polypyrrole coating. These composites have been able to reach cycling stability similar to other EDLCs.

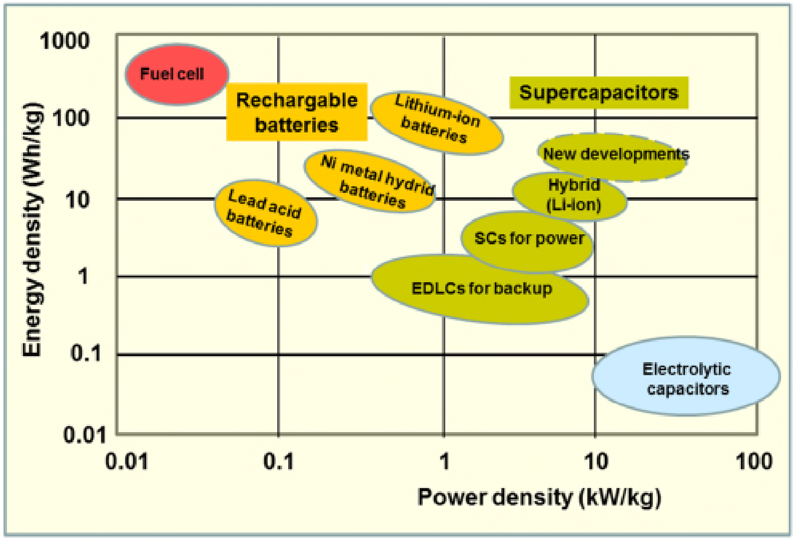

Figure 3.2 Power density vs. energy density of various capacitors and batteries [19].

3.1.11 Asymmetric

Asymmetric hybrid uses both processes Faradaic and non-Faradaic by combining EDLC electrode with Pseudocapacitor electrode. The coupling activity leads to inefficiency due to a lack of negative charges to the conducting polymer materials that limit the performance of conducting polymer Pseudocapacitors. Asymmetric hybrid capacitors have circumvented that problem by inserting negatively charged carbon electrode. Such step causes this hybrid to have a better cycling stability, high energy and power density.

3.1.12 Battery-Type

Battery-Type hybrid has a combination of two different electrodes: supercapacitor and battery electrodes. The demand for higher energy supercapacitors and high power batteries is behind this design. The use of nickel hydroxide, lead oxide and LTO ($Li_4 Ti_5 O_{12}$) as electrode and activated carbon has been the type of hybrids that has been used in experiments. Some data show that such design can close the gap between supercapacitors and batteries [10]. However, more research is needed to come up with a definite conclusion on this hybrid model.

CHAPTER 4

COMPARING ULTRACAPACITORS WITH BATTERIES

4.1 Ultracapacitors - a Complement to Battery

4.1.1 Contrast and Similarity between Ultracapacitors and Capacitors

Ultracapacitors have made a major inroad into the energy storage field. Even Tesla chief executive believes that these capacitors will supersede batteries in the near future. His statement was based on the fact that these devices can deliver hundreds of thousands more charge and discharge than the conventional battery by using their electric field instead of chemical reaction which batteries use in standard operation. The strength and weaknesses of ultracapacitors, and what needs to be done to bring them to the battery stage, is summarized below

Traditional capacitors have similar structure like ultracapacitors with two plates. But the latter is covered with porous material such as activated carbon. They are then submerged into an electrolyte with positive and negative ions diluted into a solvent. When charging, one side of the electrode is positive while the other is negative; such process is followed by the ions from the electrolyte building up on the surface of the carbon-coated plate. In ultracapacitors, each electrode ends up having two coats of ions due to the two layers on the plates. That is how researchers came up with the name “double layer capacitors” or this is like having an “ultracapacitor with two capacitors in series, one at each electrode” according to Professor John Kassakian at MIT’s laboratory. There is a reduction of ions during discharge because of the flight of electrons to the external circuit. At this point, there is a redistribution of ions to those plates as the process evolves.

4.1.2 Advantages and Disadvantages of Ultracapacitors

Ultracapacitors do not use chemical reaction to store energy; instead they use activated ions in electrolyte and bind them on electrodes to charge and discharge the energy they acquire in the process. This ability to receive and release energy as fast as it is received allows ultracapacitors to perform without major impact on their life span. The reason for such accomplishment is based on the structure of ultracapacitors, which is different from the conventional capacitor.

Both capacitors and ultracapacitors have some similarity like two plates that are separated by a dielectric that is small because there is a need to get the plates as close as possible.

Table 4.1 Advantages and limitations of lithium-ion batteries

Advantages	Virtually unlimited cycle life; can be cycled millions of times High specific power; low resistance enables high load currents Charges in seconds; no end-of-charge termination required Simple charging; draws only what it needs; not subject to overcharge Safe; forgiving if abused Excellent low-temperature charge and discharge performance
Limitations	Low specific energy; holds a fraction of a regular battery Linear discharge voltage prevents using the full energy spectrum High self-discharge; higher than most batteries Low cell voltage; requires serial connections with voltage balancing High cost per watt

The advantages and limitations of lithium-ion batteries are summarized in Table 4.1

In an ultracapacitor, the space between the plates is even closer due to the micro size of the separator. Such design allows the ultracapacitor to generate a greater magnetic field, which in turn gives more energy storage capacity. In addition to distance between the plates, the surface area also plays an important role in the device capacity to store energy [9-10]. Ultracapacitors are based on electrolytes that are used to separate the plates; they can yield more storage energy because of the level of ions that transfer through the surface area.

Besides the advantages of supercapacitors, these devices also have their limitations because they can only deliver a surge of energy, which can last from a few seconds to several minutes.

Table 4.2 Performance comparisons between ultracapacitors and lithium-ion batteries

Function	Supercapacitor	Lithium-ion (general)
Charge time	1–10 seconds	10–60 minutes
Cycle life	1 million or 30,000h	500 and higher
Cell voltage	2.3 to 2.75V	3.6 to 3.7V
Specific energy (Wh/kg)	5 (typical)	100–200
Specific power (W/kg)	Up to 10,000	1,000 to 3,000
Cost per Wh	$20 (typical)	$0.50-$1.00 (large system)
Service life (in vehicle)	10 to 15 years	5 to 10 years
Charge temperature	–40 to 65°C (–40 to 149°F)	0 to 45°C (32°to 113°F)
Discharge temperature	–40 to 65°C (–40 to 149°F)	–20 to 60°C (–4 to 140°F)

In order words, ultracapacitors cannot store energy like in a battery. However, the burst of power can help it support a battery during power surge like starting a refrigerator that is attached to a solar power system.

One analogy that simplifies the concept of the role of an ultracapacitor is by this statement [9]: “The ultracapacitor is like a small bucket with a big spout. Water can flow in or out very fast, but there’s not very much of it. The battery is like a big bucket with a tiny spout. It can hold much more water, but it takes a long time to fill and drain it.” The performance comparisons between ultracapacitors and lithium-ion batteries is presented in Table 4.2

4.1.3 Improvement of Ultracapacitors

The performance of ultracapacitors can be improved by focusing on the increase in voltage of this device. One way to achieve this goal is to increase the surface area of the plates by identifying materials that can allow the ion levels to build exponentially. The energy equation is given by:

$$E = \frac{1}{2} CV^2 \tag{4.1}$$

The goal of focusing on the increase in voltage is supported by an increase in energy. This is why researchers are experimenting with a variety of materials to see which one will get them close to their objective. Scientists are using materials such as graphene, carbon nanotubes, and other types of activated carbon in order to find the right material that can generate a maximum voltage that is comparable to battery energy or close to it.

4.1.4 Lithium Batteries

Lithium battery has been around since the 1970s and evolved as a rechargeable entity in 1980. Lithium has significant properties; first it is the lightest of all metals, possesses high electro chemical potential while having the largest specific energy per weight. During the recharging process, the anode could reach valuable energy densities that generate a level of dendrites. This relates to the cause of high temperature that leads to thermal runaway such as “venting with flame”.

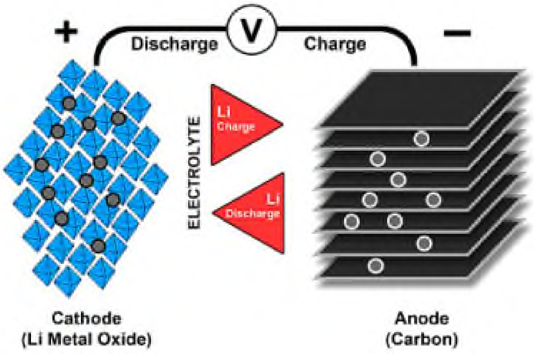

Figure 4.1 Ion Flow in lithium-ion battery [9].

Researchers have proceeded to find other means to solve this problem, which is to gravitate toward lithium ions instead of the lithium metal. Such steps allow this battery to exhibit conductive properties like current and voltage stability. Compared to Nickel-Cadmium batteries, lithium ions provide twice the energy than its counterpart. This is realized by improving the material used on the electrode. The flat discharge curve for lithium ions range from 3.7 to 2.8 Volts/cell while Nickel-Cadmium batteries fall between 1.25 to 1.0 Volts/cell.

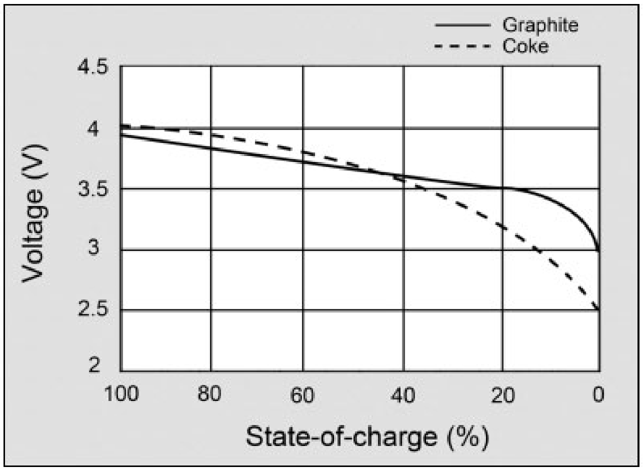

Figure 4.2 Voltage discharge curve of lithium-ion [9].

The above graph, in Figure 4.2, is a reflection of the design of Sony’s first Lithium-ion batteries in which materials such as coke were used as anode. Later design was shifted to graphite, which shows greater cycle stability when battery is charged. Scientists are also experimenting with anode and cathode to find opening in optimizing the energy capacity and increase life cycle.

There are many types of lithium batteries that have their own characteristics and are based on the materials used as cathodes. The focal point is going to be on the designs that are mostly used in the market like lithium cobalt oxide and lithium manganese cobalt oxide.

4.1.5 Lithium Cobalt Oxide

This battery is highly used for charging laptops, smartphones, and cameras. The structure of Li CoO$_2$ is based on cobalt oxide cathode and a graphite carbon anode [11]. During discharge, there is a movement of lithium ions from anode to cathode and is reverse while charging.

Table 4.3 Characteristics of lithium cobalt oxide

Lithium Cobalt Oxide: LiCoO$_2$ cathode (~60% Co), graphite anode Short form: LCO or Li cobalt.	Since 1991
Voltage, nominal	3.60V
Specific energy (capacity)	150–200Wh/kg. Specialty cells provide up to 240Wh/kg.
Charge (C-rate)	0.7–1C, charges to 4.20V (most cells); 3h charge typical. Charge current above 1C shortens battery life.
Discharge (C-rate)	1C; 2.50V cut off. Discharge current above 1C shortens battery life.
Cycle life	500–1000, related to depth of discharge, load, temperature
Thermal runaway	150°C (302°F). Full charge promotes thermal runaway
Applications	Mobile phones, tablets, laptops, cameras
Comments	Very high specific energy, limited specific power. Cobalt is expensive. Serves as Energy Cell. Market share has stabilized.

This structure allows the battery to limit its energy capacity due to concerns related to temperature and stress.

The characteristics of lithium cobalt oxide are summarized in Table 4.3.

4.1.6 Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$)

This design has been the attraction for major electric vehicle (EV) manufacturers such as Tesla, General Motors and Nissan due to high-energy capacity, good power rating and lasting for longer durations than other competitors in the market. Researchers find out that, by adding aluminum to this compound, it leads to even greater stability on the chemical side [11]. The only negative side of this invention is the high cost and some borderline safety.

Table 4.4 Characteristics of lithium nickel cobalt aluminum oxide

Lithium Nickel Cobalt Aluminum Oxide: $LiNiCoAlO_2$ cathode (~9% Co), graphite anode Short form: NCA or Li-aluminum. Since 1999	
Voltage, nominal	3.60V
Specific energy (capacity)	200-260Wh/kg; 300Wh/kg predictable
Charge (C-rate)	0.7C, charges to 4.20V (most cells), 3h charge typical, fast charge possible with some cells
Discharge (C-rate)	1C continuous; 3.00V cut-off
Cycle life	500 (related to depth of discharge, temperature)
Thermal runaway	150°C (302°F) typical, High charge promotes thermal runaway
Applications	Medical devices, industrial, electric powertrain (Tesla)

As the research on ultracapacitors and batteries are continuing, the future shows great prospects due to the increased demand for alternative energy that also addresses the need for a pollution-free world. This will lead to renewable energy sources that are suitable to the market needs of lower costs, better design and greater potential.

CHAPTER 5

Modeling Battery- Ultracapacitors for a Hybrid System - Wind Turbine

5.1 Simulation of Batteries and Ultracapacitors in a Wind Turbine

5.1.1 Use of Hybrid System to Model Batteries and Ultracapacitors

The simulation of the Battery-Ultracapacitors on a hybrid system is based on how one can predict the output of energy from wind power by using short-term energy storage in batteries that interface with ultracapacitors. The wind energy conversion system (WECS) will be modeled by measuring time series versus time resolution in one second. The purpose of the simulation is to show how the storage system will be able to balance itself even when that system experiences variable change in wind speed fluctuations. The other major factor is the inclusion of ultracapacitors in the system to overcome the sudden spike when batteries transition to charge and discharge mode. Ultracapacitors respond positively during short transient in energy flow while minimizing the impact in battery life. The structure of the model for the simulation of short-term storage system for the wind energy conversion system through a SIMULINK design [3] is investigated here. At the start, the wind energy conversion (WECS) system is generated to measure the time series with a time resolution of one second. The next step is to calculate the power that has to be exchanged with the storage system. By taking the difference between the actual wind power and the predicted one, it is represented by the equation below.

$$P_{st}\,(_t)= P_w\,(_t)\ -P_p\,(_t) \qquad (5.1)$$

where t = present time, P_{st} = the power input storage, P_w= the measure of wind power output and P_p= the predicted power to grid.

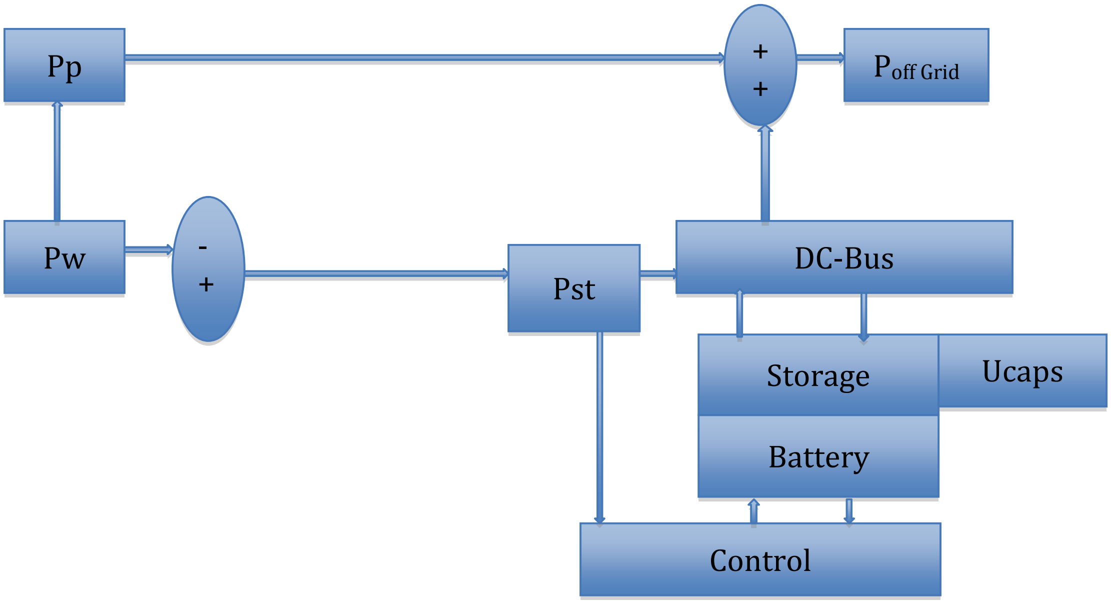

Figure 5. 1 Structure of the SIMULINK model for simulation of a short-term storage system for WECS [3].

Using the worst-case scenario, this model takes P_p the predicted power, due to the fact there is no information on future wind speed, to assume the type of wind power that will be generated [3]. Such assumption leads to some error in the prediction that the system takes into account through simulation. The storage capacity will allow the system to compensate for any fluctuations that occurs. Starting with a time interval of I, the output power in the future will then be t + I while the average power output of the past time falls in the range of t – I. This procedure is defined as the average power with respect to time interval I. To solve the actual power exchange with the storage, the time lapsed is taken from t – 2I to t – I. The predicted power will be written as:

$$P_p(t) = 1/I \int P_w(t)dt \qquad (5.2)$$

where, t falls in the range t-2I and t-I.

This leads to the result for storage power as shown below:

$$P_{st}(t) = 1/I \int P_w(t)dt - P_w(t) \qquad (5.3)$$

where t falls in the range t -2 I and t-I.

The storage power P_{st} can be positive (discharge) or negative (charge) [3]. The following step describes how the DC-bus interacts with the wind energy conversion system and the grid. There will be losses occurring during this process. However, the battery placed parallel to the ultracapacitor would be used as buffer to compensate for the peak voltage that is generated during wind speed fluctuation.

$$I_{bat}(t) = I_{st}(t) - I_C(t) \qquad (5.4)$$

The battery input current is represented by the difference between the storage and capacitor currents while its output are the battery voltage, its temperature and state of charge (SOC).

where,

I_{bat} = Current in the battery ;

I_{st} = Storage current;

I_C = Capacitor current

$$I_C\ (t) = I_{bat}\ (t) - I_{st}\ (t) \quad (5.5)$$

with I_C (t) depending on the derivate of V_{dc} :

$$I_C\ (t) = CV_{dc}(t)/dt \quad (5.6)$$

Equation (5.6) shows the slow increase in the voltage in capacitor C as the level of currents into or from the capacitor decreases. For C = 10 F, a rate of voltage change of $dV_{dc}/dt = 10$ V/s results in a current in the capacitor of $I_C = 100$ A. In the reverse case, any peak in current creates only a small change in voltage. This damping effect prolongs the battery life significantly. This is one quality that greatly favors the consumer. The total storage current I_{st} is defined by the DC-bus voltage V_{dc} and the storage power P_{st}

$$I_{st}\ (t) = P_{st}\ (t)\ /\ V_{dc}\ (t)/dt \quad (5.7)$$

According to the Department of Electrical Engineering at the University of Zaragoza, "a control unit prevents the battery from hazards due to high currents or voltages, over charge and deep discharge. If the permitted current, voltage or SOC limits are reached, a storage error P_{SE} is generated. This error means a deviation from the predicted wind power because it is assumed that the energy which cannot be stored in the storage system is injected to the grid". From the storage error, a prediction error PE is defined:

$$PE = P_{SE}\ (t)\ /\ P_p\ (t)\ dt \quad (5.8)$$

Bidirectional DC/DC Controller

The role of the control unit in this system is to regulate the amount of power that is acquired and transported to the load. This entire apparatus is also controlled by the state of charge (SOA), the battery temperature and the change between predicted and actual wind factors. This model has been modified to its simplest form in order to reduce its complexity. The integration of the ultracapacitors module is considered as short-term energy storage while the battery is considered as long-term energy storage. The ultracapacitors module is connected to the DC link of a permanent magnet synchronous generator link to the wind turbine through bidirectional DC/DC controller. The battery is connected to the DC link through the second DC/DC link controller. The role of this controller is to keep the voltage of the DC link constant as a reference value. This DC/DC controller functions in various modes.

A) When the DC link voltage V_{dc} is greater than the reference voltage, DC/DC controller regulates the amount of current that charges the ultra capacitor.

B) When the DC link voltage V_{dc} is less than the reference voltage, in this mode, the ultra capacitor discharges.

C) However, when the ultracapacitor is fully charged, the controller shuts off so the ultra capacitor is not over charged or damaged.

D) When the ultracapacitor is fully discharged, the DC/DC controller opens the current line to allow the capacitor to resume charging.

Power smoothing is achieved by using two high pass filters with different cut-off frequencies. The high-pass filter with lower cut-off frequency computes the amount of power that will be stored or supplied by the battery with the ultracapacitors module. The high-pass filter with higher cut-off frequency calculates the amount of power used by the ultracapacitors module. The energy stored or released from the battery is based on the difference between this output power and predicted power.

The hybrid system behaves differently at different time intervals while operating at various wind speeds. Based on previous experiments, wind power tends not to change erratically. Due to this precedent, the frequency range of 0.1 to 10Hz is considered acceptable for a stable energy system. This leads to the conclusion of considering wind data of one second as sufficient. However, the level of data needed to support this simulation has to go beyond second; but it has to reach an hour limit in order to have data that are concrete and tangible.

Table 5.1 look at the system economically in terms of the benefit one can acquire by investing in a wing power generator. The conclusion is that it only cost about 5% of what they invested on. That is considered as economically feasible or worthwhile. Also, the power generated to grid is more stable compared to the output wind power because of the inclusion of the short-term storage of the ultra capacitors.

Integration of Short-term Storage

This model shows that the integration of short-term storage is viable way to make the wind power system more efficient due to the fact that Ultra capacitors reduce the cycle between charge and discharge, which affect the longevity of a system that rely strictly on battery. In addition, the inclusion of ultracapacitors allows the wind energy generator to perform smoothly because the ultra capacitors absorb the current spike that wind variation causes during day to day operation.

Estimated Number of Cells

Table 5.1. - Estimation of needed battery size to cover the calculated time series P_{st}

Time Interval	Power Restriction	Energy Restriction	Final Election
10s	188	105	188
30s	236	169	236
1min	244	210	244
5min	264	264	264
10min	264	330	330
30min	276	575	575
1h	404	1010	1010

After simulating different time intervals while looking at power and energy restrictions that are tabulated in Table I, the result shows that based on the estimated number of cells or battery size how much output power will be generated from the system.

An Economical Evaluation of the Battery Systems at Different Time Intervals.

Table 5.2. Economical evaluation of the battery system

Time Interval	Number of cells	Energy Capacity [KWh]	Battery System cost [€]	Cost relative to WECS [%]
10s	188	94	18800	3.1
30s	236	118	23600	3.9
1min	244	122	24400	4.1
5min	264	132	26400	4.4
10min	330	165	33000	5.5
30min	575	288	57500	9.6
1h	1010	505	101000	16.8

Table 5.2 compares the value of the battery-operated system to the ultra capacitor set parallel to the battery. The voltage is fluctuating greatly when the battery is the storage system for the wind generating system; however, the change is drastic when the ultracapacitor is placed parallel to the battery, the level of fluctuation is minimal with a bank of 240 ultracapacitors connected in series. The energy capacity of the battery is at 315kWh with a rated power of 31.5kW while the ultra capacitors have an 1872kW at 0.72kW. This simulation outlines the great advantage that ultra capacitors provide to a

stable and efficient system.

5.1 Battery and Ultra Capacitor Data

Table 5.3. Battery and ultracapacitor data for the storage system

	Battery	Ultracapacitor
Number of Single Cells	300	240
Rated Capacitance	500Ah	10F
Rated Voltage	630V	672V
Maximum Voltage	720V	720V
Rated Power	31.5kW	0.72kW
Maximum Power	150kW	1872kW
Energy Capacity	315kWh	0.63
Lifetime (cycles)	1500	500000

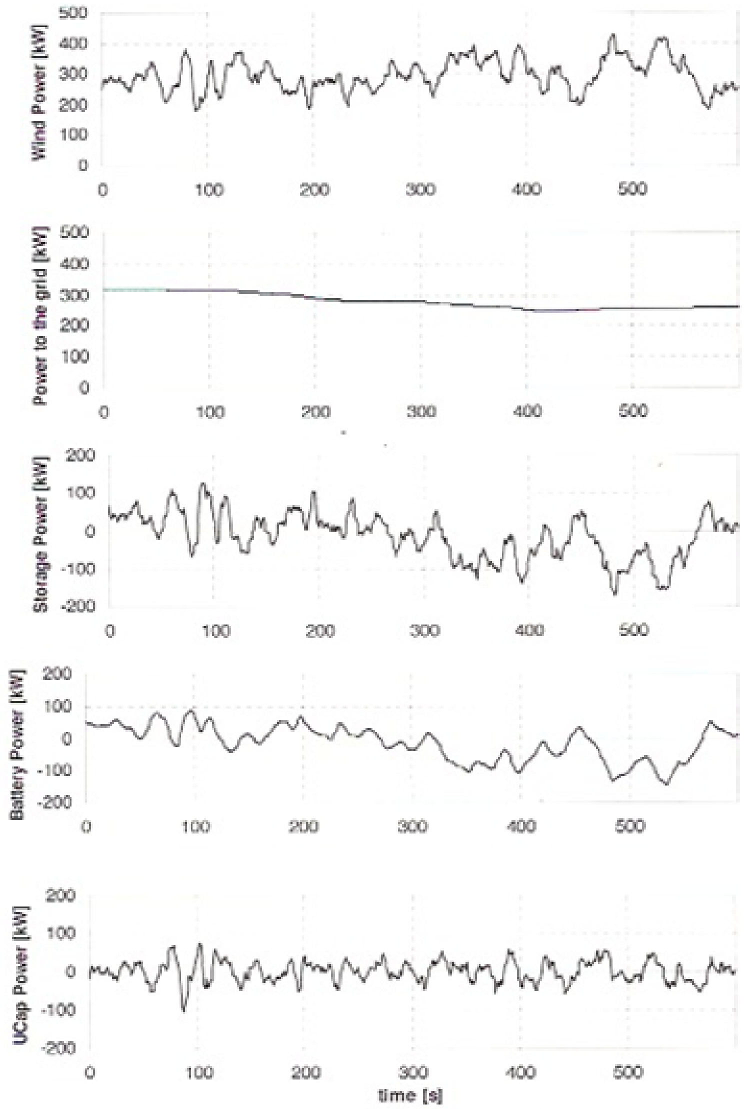

Fig. 3. Simulation results for the battery system with a 10 F ultra capacitor bank designed for a 10min time interval. From above: total input power to the storage system, input power to the battery, input power to the ultra capacitor bank.

Figure 5.2 Simulation results of battery system with a 10 F ultracapacitors bank designed for an interval of 10min. From above: total input power to the storage system, input power to the battery, input power to the ultra capacitor bank [3].

CHAPTER 6

APPLICATIONS OF ULTRACAPACITORS ON VARIOUS ENGINEERING DESIGN.

6.1 Manufacturers Usage of Ultracapacitors

6.1.1 Ultracapacitors in EV

Ultracapacitors capture the attention of many manufacturers that are searching for an alternative way to store energy that could be released at a moment notice. Many engineering design have to deal with electromechanical system that tend to give off excess power at time that is unexpected [12]. These power surges usually cause a lot disruption and damage that turn out to be costly to these companies.

Ultracapacitors becomes the solution to those ills because ultracapacitors allow engineers to absorb those vicious surges and keep their system functioning without any interruption. Ultracapacitors has the ability to charge and discharge multiple with great impact on their life span. Such characteristic can’t be applied for batteries, which degrade through usage. Even though ultracapacitors can be used to support electromechanical system, but they still can reach the storage level of regular batteries. That‘s why they are being integrated with batteries to make the whole system more stable. Applications for this product can be found on a variety of machines such as electrical vehicle (EV), automated meter readers, digital cameras, wind turbines, static energy storage system, and hybrid electric buses.

6.1.2 Electrical Vehicle

Engineers use ultracapacitors in electrical vehicle to control acceleration and deceleration of the vehicle while minimizing energy loss and degradation of battery. This is accomplishing by connecting an Insulated-Gate Bipolar Transistor (IGBT) buck-Boost converter to the ultracapacitors pack at Boost side and to the main battery at Buck side. The energy stored in the ultracapacitors is monitored by a control system that checks the incoming voltage, and current in both terminals [5]. In addition, a microprocessor deals with what is occurring behind the scene like the Pulse Width Modulation (PWM) switching pattern of the IGBT. When the vehicle is idle the capacitor bank stay fully charge; however, when the car is moving at high velocity, the control allows the capacitor to discharge. To know the battery voltage is to known how much power the car can generate as far as acceleration or deceleration. This data allow the controller to activate the Buck converter to store kinetic energy of the vehicle in the ultracapacitors. A charge battery leads to system to keep the ultracapacitors at mid charging level and visa versa. Also, an IGBT controlled power resistor is placed in the converter to block energy from reaching neither the ultracapacitors nor the battery pack in unwanted circumstances [5].

6.1.3 Wind Turbine

Wind turbine consists of three blades and variable speed turbines. An independent electromechanical propulsion unit that drives the pitch control system does the control of the blades. The output power is monitored in order to balance the blade speed when the wind turbine is running high. If the blade pitch fails on one unit, the remaining blades based on the system design will keep the system in operation [5-6]. To create a greater level of safety in that pitch system, an emergency power pack is needed to make the wind turbine stable in hazardous situation.

Batteries are mostly used when there is a need for emergency power. However, batteries tend to fall short during high power demand due their limitations when it comes to satisfy peak power surge that requires quick response in a matter of seconds. This is when ultracapacitors comes into play because they have characteristics that can support power surges that happen at unexpected time. Besides, their ability to charge and discharge continuously without impacting their life span make them the ideal candidate for the wind turbine system. Some of these turbines are placed in off shore location, which will make them hard to maintain if they have components that are failing consistently. They work well in extreme condition as far as temperature is concerned, they are small in size, and very cost effective when compare with batteries.

Ultracapacitors are the ideal component for the wind turbine system because they are maintenance free device that does not need to be inspected regularly. They can work as a complement to batteries that can handle high power surge. Such attribute allows them to act as a buffer when there is a need for delivering or receiving high currents [5-6]. They last longer and when pairing with batteries, they increase the battery life span due to the fact they absorb power surge that can be detrimental to those batteries longevity. Finally, they are reliable because they are there to ensure the need of the blade pitch system is met when the demand for high power arises.

6.1.4 Ultracapacitors Support P_{21} to Power Telecom

P_{21} supplies fuel power to telecommunication companies as a back-up system. They used conventional batteries to support the base station network they operate remotely. P21 is searching for alternative energy storage to back up their system that requires a few second to come online. The best candidate for this task become ultracapacitors because they want a component that have storage capacity, so that their mobile phone base stations have continuous power as the need arises and without interruption when the electrical grid is off. Even though fuel cell are excellent energy conversion devices that support the load as long as the hydrogen gas is present to power the base telecom stations [19]. Their reliability and cost saving give them the upper hand in that category; however, at five seconds, fuel cell can reach full power but cannot sustain this output power without the help of a source bridge power to make sure that based stations can continue to function without interruption. Attached to that source bridge power is an energy storage component such as batteries or ultracapacitors. Let’s look at batteries in that setting, they become an issue due to the constant need to be maintained, they do not operate efficiently in extreme temperature while these P21 based stations are located remotely from the main company hub. Under such condition, a good candidate must be ultracapacitors because of their excellent characteristics such as low ESR, high charge storage capacity. They can also handle high current, and have buffer that can support quick response during peak demand. So, P21 coupled with ultracapacitors can operate efficiently with smooth transient power. The other advantages ultracapacitors have over batteries are those they can adjust their output with respect to the load that they are dealing with. In addition, they are cost effective, low maintenance and last longer than regular batteries. Besides, P21 energy cost was reduced due to the fact that there was no need for air conditioner to keep the system cool during extreme weather.

Ultracapacitors represent the perfect match for P21 system because they provide the back-up necessary to keep the system operational without stoppage. Their features are aligned with the demand of P21 fuel cell system compared to traditional batteries

CHAPTER 7

Making Ultracapacitors More Marketable

7.1 Higher Demand for Storage Capacity in Electric Car

7.1.1 Start and Stop Design to Enhance Ultracapacitor Usage

When looking for the best performance and highest safety record, these are the attribute of ultracapacitors. Due to high demand for electric and hybrid vehicle, manufacturers are searching for tools that would make these cars more fuel efficient at reduce cost. Such goal will allow them to meet the demand for efficiency while maintaining and improving performance that consumers are searching for [17]. The need for hybrid and electric vehicle is based on the continuous rise of fossil fuel and customers are looking for a way out by migrating toward alternative energy storage such as batteries coupled with ultracapacitors that could cut down on their consumption of gasoline and still carrying the safety that they accustom to.

Engineers have come up with ways to improve on the fuel economy on EV cars by installing start and stop systems called micro hybrid vehicle (MHV). The role of the start and stop features is to stop the motor when the car make a complete stop and restart when the car is moving again [5]. This simple system is able to increase fuel efficiency by 10% in city driving. Besides, this feature can work with the adequate software that can synchronize the timing between mechanical and electronic components within the car. However, the major hurdle of batteries is that they can’t handle the task at hand because they can't respond fast enough to the demand of an electro-mechanical system. The battery temperature tends to be unstable which make unsuitable to operate in any environment that experiences constant change in temperature that can vary from one extreme to another. In addition, there is a weight factor that car manufacturer want to reduce in order to have a better fuel efficiency. The only battery design that is a better alternative to the standard battery is AGM batteries that has the characteristic of standard SLI batteries

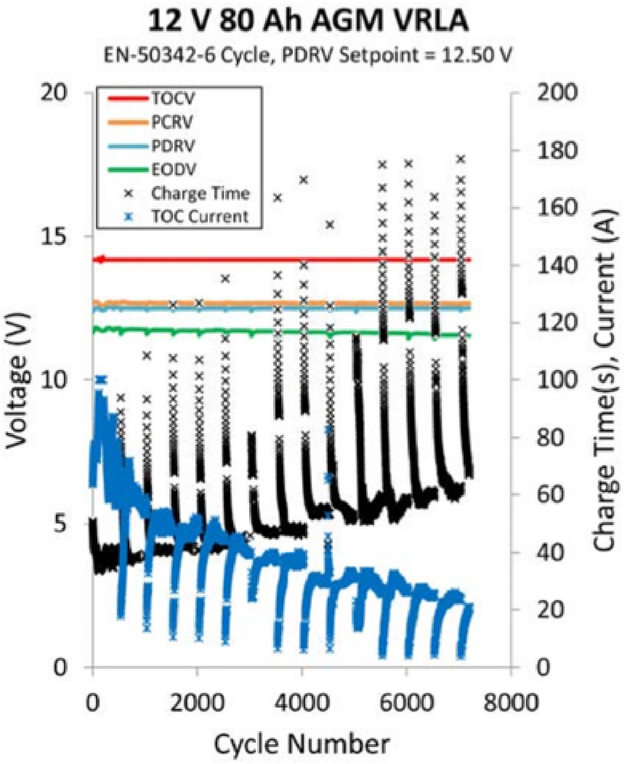

Figure 7.1 AMG EN-50342-6 [19].

This graph show the performance of the AMG batteries that provides acceptable result at the beginning; but such expectation declines due to the sudden surge of power that impact the output of the life cycle of the batteries [19]. In order to bring the battery back to full potential the unit has to remain idle for a long period of times which is not feasible to the consumers who can afford to wait that long. Ultracapacitors were also tested to compare their output with the battery. The result was very impressive because it shows that these capacitors can perform 100,000cycles more than batteries.

Costs For Auto Energy Storage System		
60 Ahr SLI Cost	$	50
60 Ahr AGM Cost	$	110
60 Ahr Lithium Battery Cost	$	500
30 Ahr SLI Cost	$	32
Capacitor Module and Controls	$	325
Capacitor System cost (w/battery)	$	357

Figure 7.2 Current component costs for Auto ESS [19].

In addition, the fact ultracapacitors can vary with a wide range in temperatures, which AGM batteries can't. In addition to cycle time, OEM mainly focuses on cost and warranty which are the parameters that consumers look for when buying a product. Battery safety is a major concern due to ongoing disaster that happens and the battery that either caught fire or explodes caused the main failure. Figure 7.2 provides an overview of the cost of current components that goes into Electric and Hybrid Vehicle.

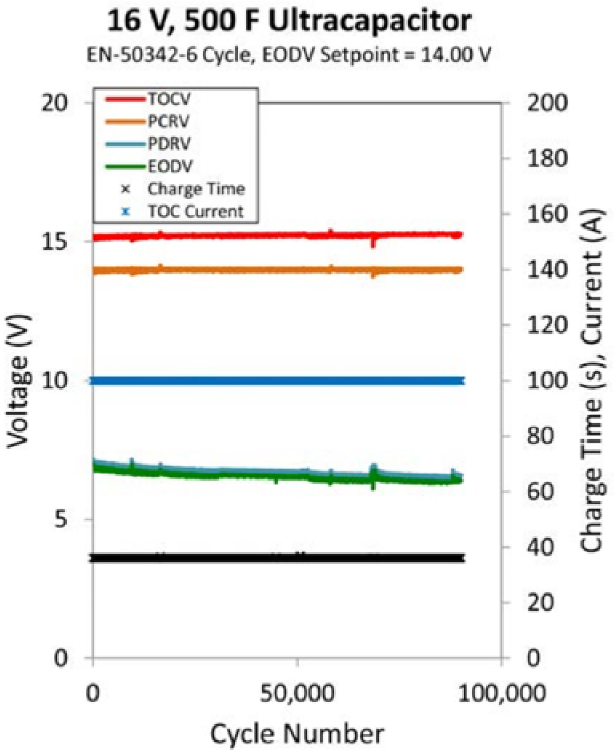

Figure 7.3 Ioxus EDLC performance EN- 50324-6 [19].

		SLI	2x SLI	AGM	2x AGM	Lithium	Ultracaps
Cycle life	Cycles	500	500	800	800	1500	500000
Start stop cycle depth	%	5	2.5	5	2.5	5	50
Warranty	Yr	3	3	3	3	3	3
Maximum Product Life	Yr	5	5	5	5	10	20

Figure 7.4 Warranty and usage [19].

Figure 7.4 depicts the warranty and life cycle of SLI, AGM, and Lithium batteries compared to Ultracapacitors [19].

CONCLUSION

Ultracapacitors innovation will challenge the mainstream energy on earth, which is fossil fuel. The fact, that Ultracapacitors can be charged as fast as someone filling up her or his tank on gasoline pump station, will drive the automobile, electronic, and computer industries to gravitate toward the use of ultracapacitors as a complement to batteries. This technology is at its infancy because the companies in that market have made great stride with goal to improve it as the years go by. The trend for this technology is evolving with lips and bounces when looking at the chronological steps that occur over a decade. The interest is worldwide because such discovery will also have a great impact on one of the major problem the world is facing today is pollution caused by fossil fuel industry. The cost of this technology is also not expensive due to the fact that some of the materials such carbon nanotubes, graphite, lithium, and titanium dioxide are readily available and can be extracted at low cost to build Ultracapacitor batteries as the alternative energy. The modeling of Ultracapacitors for an off grid solar energy showed how efficient this system can be used as a backup system or for regular usage on residential properties. The discovery by scientists at Nanyang Technology University shows the promises that Ultracapacitors will provide to the world when it comes to fast-charging batteries to 70 percent in just two minutes. Wind turbines would also enjoy the benefits of such advances because they also can store unused energy that can be used in emergency cases. SolidEnergy Systems used lithium-metal electrode design that would eventually double or triple the driving range of EV. This design is to build a cost effective battery that is used polymer and ionic liquid that would allow such battery to charge and discharge quickly. Rural areas are greatly affected by energy usage due to lack of infrastructure available in their zones. This type of technology would allow those communities to build their own power station that could provide the needed energy for them to grow. The main ingredient about this green technology is that it does not pollute the air that we breathe. Ultracapacitors cover a wide range of industries from houses, transportation, electronic, and the positive impact it offers when it comes to deal with earth environment.

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