Conceptual Design of a Battery Pack for Use in a Mobile Hybridized Power Generation System

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Abstract

Mobile generation platforms are very common among both military and civilian applications. However, in military applications getting fuel to the front lines can come at a very high cost. This cost is both financial, costing upwards of hundreds of dollars a gallon, and human, with resupply convoys being the leading cause of casualties in today's warfront. Diesel generators operate much more efficiently at higher loads, rather than the lower loads that the systems normally operate at. To improve fuel efficiency, a hybridized generator system is proposed. This system combines a standard generator with a large rechargeable battery pack. The addition of the battery pack allows for several unique power scenarios to occur through power generation. The battery pack functions to provide an efficient storage capability for the system. During times of excess load, the battery and generator work together. This allows for algorithms to manage the generator set to operate at peak efficiency while addressing load spikes. A system like this has been theoretically designed and a simulation has been developed to determine the impact over a standard system. Actual load cycle information from military sources has been used to evaluate the concept. The results of the simulation show increase efficiency, in the low load scenarios, to more than double the standard generator efficiency.

Acknowledgements

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Nomenclature

State of Charge: (SOC) A percentage of the present battery capacity compared to the maximum battery capacity. It is usually calculated using current integrated over time.
Depth of Discharge: (DOD) A percentage of the battery capacity that has been discharged compared to the maximum battery capacity.
Nominal Voltage (V): The voltage that the battery is reported or referred to as.
Cut-off Voltage (V): The lowest voltage the battery can safely drop to. The cell is usually referred to as empty or fully discharged at this point.
Terminal Voltage (V): The voltage between the battery terminals when load is applied. Terminal voltage changes depending on SOC and charge or discharge currents.
Open-circuit Voltage (V): The voltage between the battery terminals, without a load applied. Once the battery has reached steady state, the open-circuit voltage depends on state of charge.
Charge Voltage (V): The voltage the battery uses to charge to 100% SOC.
Float Voltage (V): The voltage the battery uses to maintain charge after reaching 100% SOC.
Recommended Charge Current (A): The ideal current at which the battery is initially charged, usually until about 70% SOC.
Internal Resistance(Ω): The resistance of the battery itself, usually different for charging and discharging; it also depends on the battery SOC. As the resistance increases the efficiency decreases.
Capacity (Ah): The total number of Amp-Hours available in the battery from 100% SOC down to the cut-off voltage.
Energy (W-hr): The total number of Watt-Hours available in the battery from 100% SOC down to the cut-off voltage.
Cycle Life (#): The number of full discharge to full charge cycles the battery can run before it fails to meet performance characteristics. The battery is usually considered "unfit" when it fails to maintain an 80% capacity rating.
Specific Power (W/kg): The available battery power per unit mass. This is a result of battery chemistry and pack construction.
Energy Density (Wh/L): The battery energy per unit volume. This is a result of battery chemistry and pack construction.
Power Density (W/L): The battery maximum power that is available per unit volume. This is a result of battery chemistry and pack construction.
Maximum Continuous Discharge Current: The highest current the battery can be loaded at continuously.
Maximum 30-sec Discharge Pulse Current: The highest current the battery can be discharged at for a time of 30 seconds.
C Rating: Used as a common method for current levels for the battery pack. The C rating is the one hour discharge rate.

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Chapter 1: Introduction

For the first time the Department of Defense (DOD) has developed a strategy to transform the way the department consumes energy in military operations. [1] In 2010 alone the U.S. military consumed more than five billion gallons of fuel in military operations. This seems to be due to the nature of the current missions, having such a broad range of operations and capabilities. While this strategy is happening the military demand for energy is continuously growing, leaving supply lines under pressure. Over the last few years the fuel logistics of resupply have proven vulnerable to attack in recent conflicts. [1] As long as the military depends on large amounts of energy, mostly JP8 fuel, the vulnerability remains in the system. The primary goal of the implemented strategy is to provide the armed forces with the required energy to meet current challenges.

It would appear that the DOD has come to the realization that to maintain the presence it has demonstrated over the last decade it needs to change the way energy is dealt with during conflict[1]. In 2007, in Iraq and Afghanistan alone, more than 3,000 Army personnel and contractors were wounded or killed in conflicts resulting from attacks on fuel and water resupply convoys. A reported 1,100 ground convoys were attacked in 2010, and this number may not include the transportation of fuel from a forward operating base to various patrol bases. To deal with these issues some fuel supplies are rerouted or even delivered via helicopter to minimize risks to the convoys and ensure arrival. Air transportation of fuel can be used, which costs ten times as much as ground delivery. The new initiatives could greatly reduce our battlefield fuel demand through the use of new clean energy technologies, thereby saving lives and saving money.

The DOD is one of the world's largest institutional energy consumers, using more than 300,000 barrels of fuel daily, which exceeds the consumption of more than three-quarters of the rest of the world. In 2008 alone, the energy cost for the DOD was $17.9 billion. Figuring out the actual cost for fuel use in conflict is more than just the cost of the fuel itself. While the military fuel is purchased for $2.82 per gallon the fuel can cost $13 if it is shipped by ground to a foreign location during a time of non-conflict. If fuel is transferred via aerial refueling the fuel costs $42 per gallon. If the fuel is transported to an area of conflict the fuel can range from $100 to $600. The Army estimated a fuel cost of up to $400 per gallon if the only way to ship is by helicopter. [2]

These vastly different estimates help to explain why it can be a difficult task to precisely calculate the price of military fuel. The Pentagon has been trying to figure this out for years, but has not come up with an easy answer. Within the past decade, two studies have criticized the Pentagon for not having a reliable way of measuring the "fully burdened" cost of fuel. [2]

Over the last few years, the military has announced several aggressive energy goals to reduce the overall consumption of energy, reduce the need for foreign oil, and increase the use of alternative energy. The purpose of these goals is to improve combat capability and increase our energy security. There are multiple projects over all of the branches of the military to help accomplish these goals. For example, the Navy is developing a carrier strike group, known as the "Great Green Fleet," which will be fueled by alternative energy sources. There are many technologies the fleet will use to achieve the given mission statement. Some of these technologies are solid state lighting, gas turbine in-line water wash, shipboard energy dashboard, and smart voyage planning decision aid.

Not all projects in the works are of this magnitude; some are much smaller projects being worked on to achieve the same goal. One such project is the Hybrid Electric Autonomous Tactical Support system, or the HEATS system. This is the system which this paper describes. The HEATS system is used as the theoretical development platform for testing of a hybridized generation system. The platform used has a long history of experimental platform development, originally donated by Ingersoll Rand to be used for autonomous research for the DARPA Grand Challenge. After the DARPA project the vehicle platform was “temporarily retired” for a few years. It remained unused until the academic school year of 2011, where a group of researchers used the platform for senior design research. That year the vehicle began design to be a proof of concept for a series hybrid off-road autonomous vehicle platform. The current state of the vehicle can be seen in Figure 1-1. This is the platform that will be designed around for this paper. The vehicle system will be treated as a mobile generation source, essentially a series hybrid vehicle with no traction motor. This paper will go into detail about the design process and simulation results.

Figure 1-1: Current state of the HEATS vehicle system

The proposed hybridized generation system consists of three primary sections. These sections include the on-board generation system, the battery pack, and the power output, or the load onto the system. The interactions between all of these can be seen in Figure 1-2. For the purpose of this project, the generator can be used to supply power to the output load, charge the battery pack, or a combination of them both. The battery pack can take in power from either the generator or from a variety of scavenged power. It is the unique variety of power flows through the system that gives the hybridized system an advantage over the standard system.

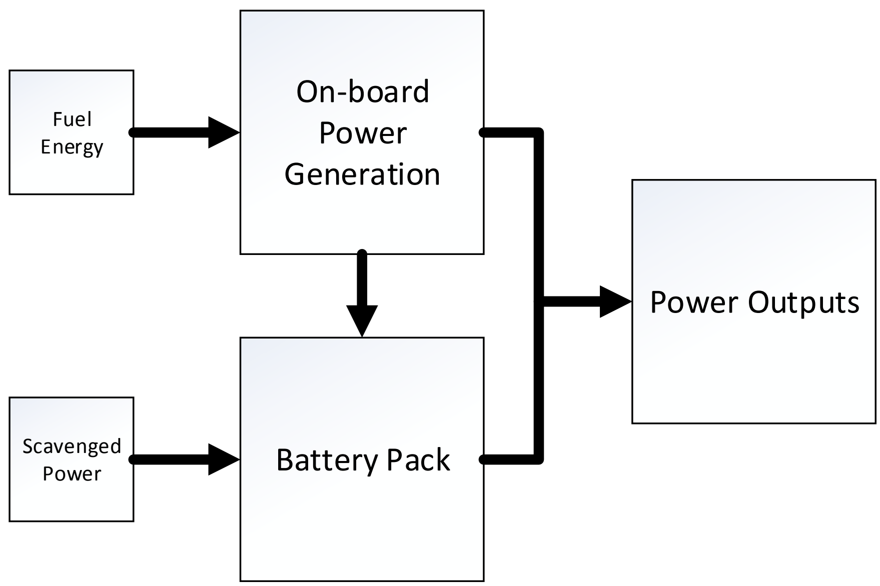


Figure 1-2: Block diagram for the overall basic system for the HEATS project.

The goal of this thesis is to review the several different aspects for the design of the hybridized power generation system. The following system design has been split up into five different sections for the entire system design. The first section that will be discussed is the literature review, which summarizes much of the background information for the remainder of the paper. This includes defining the problem and the requirements that have to be met as well as reviewing the basic overall system including energy generation, storage, and output. The following section, energy storage, reviews battery chemistry and battery pack design. In this section the most appropriate battery pack, considering both chemistry and size, is selected. These results may not be the same for every scenario, but to compensate for this a battery selection equation has been developed. The following section addresses battery management. This section goes into detail about the design for the battery state of charge calculation, battery balancing, protection circuits, and system integration of all of the parts. Next the power input section describes the requirements that are necessary to meet all of the requirements to be able to take advantage of a variety of power inputs. This includes the variety of inputs that can be taken advantage of and how they are utilized. Also in this section system simulations have been developed to determine how beneficial the hybridized system is over the standard generation system. The final section describes the power output from the system. Similar to the section before, it also reviews the multiple outputs the system can handle, and how it is accomplished. Additionally, the inverters and converters are selected and sized. The result of this design would be an increased efficiency mobile hybridized generation platform that has the ability to accept and supply a variety of power options.

Chapter 2: Literature Review

2.0 Chapter Summary

This chapter summarizes much of the background information for the power inputs, the battery storage, and the power outputs parts of the design. The first section of this chapter helps determine the scope of the problem. This section reviews the kinds of scenarios the system would be used in, mostly analyzing different kinds of military encampments and their respective power requirements. This section also reviews the generalized proposed system, dividing the project into three basic subsections. The first is the power generation and input sources for the project. This section reviews how energy is generated using a basic fuel generation system, which is essentially a diesel engine in tangent with an alternator. This section also reviews the different kinds of scavenged power that would be available. The second subsection of the project is the energy storage section. This section reviews the types of possible battery chemistries that could be used and it also includes a characteristics table. The third, and last, subsection is the power output systems for the project. This discusses how the power output from the system is normally handled, using converters/inverters to meet standard power ratings.

2.1 System Environment

The armed forces have a variety of different size encampments requiring vastly different amounts of power. According to the DOD, the encampments are set up as semi-permanent structures and require well-supported power generation systems to operate This section contains a review of several of these encampments, as well as an analysis of their power needs.

Figure 2-1: Example image of a FOB. [3]

One of the largest encampments considered is a Forward Operating Base (FOB) that normally houses three rifle companies, artillery, and battalion command elements. The FOB also usually has a thousand Marines stationed there at any time and has quite large power requirements. Current FOBs are usually powered by three large on-site generators, usually between 20-30 kW.[4] While these generators can supply a large amount of power for mobile operations, on normal partial-load cycles the generators run very inefficiently and waste a lot of fuel energy in the conversion. The DOD is currently developing what they have dubbed the ExFOB, or Experimental Forward Operating Base, where they are working on reducing external logistical power requirements. In this testing the FOB ran two 120,000 BTU/hr environmental control units (ECUs) three 36,000 BTU/hr ECUs, a small refrigeration system and numerous smaller electronic loads, such as laptops and communication systems. Research has shown that the refrigeration and air conditioning system tend to require the majority of the power. [4]

A slightly smaller encampment, a Company Outpost (COP) usually has three rifle platoons, a motor group, and a company command element. The amount of required power can highly vary at these outposts depending on scope of the mission and the duration of the stay. According to DOD specifications the load potential at a COP for the essential equipment can contain a refrigeration unit (5 kW), G-BOSS (3.2 kW), radio equipment (1.7 kW), plus the addition of multiple smaller loads summing up to a total load of about 14 kW. [4] Power is usually supplied using multiple 2-3 kW generators running at less than optimal conditions.

A patrol base (PB) is an outpost of the company outpost and has a significantly smaller power requirement. The PB is used as a base of command for local squads to perform patrols around. The average load consists of laptops, printers, lighting and individual power requirements, totaling an average power requirement of about 1.5 kW. [4] Most patrol bases do not have a generator on site, requiring all loads to be run off battery and therefore requiring resupply to stay active.

Observation posts (OP) are operated from the patrol base and are usually in locations that are near local civilians or in locations of enemy activity. This encampment is the smallest of the units that the Marine Corps uses, and is used to keep surveillance of an area. The OP can be located anywhere from a small rural area or in denser populace. Much like the PBs there are no generators at the OP. They require battery power for all the systems. Due to the variety of uses the OP can offer, an estimated power usage has not been provided, but the system must have enough power for communications and optics at a bare minimum.[4]

The military also maintains the use of checkpoints in areas to maximize security. These checkpoints are manned and operated all day and require enough power for communication systems, sensors, and adequate lighting. Most checkpoints are powered using 2 or 3 kW generators.[4] The military also uses what they have called Combat Engineering to increase security. Combat engineers do anything from construction to road clearing. To operate the average checkpoint efficiently, 10 kW appears to be adequate.[4]

Looking at all of the different encampments the military uses regularly, it is impossible to meet the energy requirement for every military scenario. Knowing this information the proposed project will be using an efficient 10 kW generator. While this number does not meet all of the power requirements for all of the bases it does meet most of the requirements for a variety of bases and stands as a good proof of concept system

2.2 Power Input/Generation

The main goal of this project is to be able to efficiently create and store energy from a wide range of sources. These sources include, but are not limited to, an on-board fuel generator-set, renewable energy systems, 120 VAC wall power, and additional scavenged power. In this paper an exact power generator set has not been chosen, however the generator size required has been taken into account for the overall battery pack design.

A generator set is described as a machine that converts mechanical energy, supplied by an engine, into electrical energy used for either recharging the battery or supplying power to the electrical system. There are multiple techniques that can be implemented for energy generation. Two of the most popular techniques are generation via fuel cell and via generator set. A fuel cell is a device that converts the chemical energy from a fuel into electrical energy through a chemical reaction. However, for this type of application standard generator sets (gen-sets) are the most common. For this reason generator sets will be used for the on-board generation requirements. When the engine is at low speeds, or even idle, the generator has a low, or even zero, power generated so the battery would be required to provide all the electrical energy needed. At a higher rpm the gen-set is capable of producing a significant amount of power, until a point at which some generators will actually drop off in power generation.

All generators create energy in much the same way, based on the principle of electromagnetic induction. The voltage is generated when any conductor moves through a magnetic field, where power generated is the perpendicular component of movement. When the voltage is created in this manner, it will create current that flows in the conductor if that conductor is a complete circuit. [5] For the purpose of this project, additional information on the science behind power generation is not required.

Generator sets are a common item in industry and are available in a wide range of specifications. These include small, hand-portable units that can generate hundreds of Watts, hand-cart models that can supply thousands of watts, and stationary or trailer mounted units that can supply over a million Watts. Non-dependent on size, gen-sets can have the capability to run a variety of fuels including but not limited to, gasoline, diesel, JP8, natural gas, propane, bio-diesel, and hydrogen. For the scope of our project the designs are limited to generators that operate on diesel and JP8. JP8 is the standard for military vehicle and generator fuel. [1]

There are many different generator configurations possible to complete the mission goals. The first of which is simply to have a large enough generator to produce the maximum required power for the encampment. This is the style that is currently used and, as established earlier, they usually run very inefficiently. The second is sizing a slightly smaller generator, which would run more efficiently at lower loads, but would require a battery pack buffer for higher load demands. At lengthy high load periods of time, however, lower priority loads may have to be dropped to ensure stable power for primary loads. Also, two smaller generators could be used, and only running two at high load demand times. This concept is interesting in the fact that it could maximize efficiency with the battery pack but would require significantly more power circuitry to manage both power sources. Each set has advantages and disadvantages to the system; however, for this project one large generator has been selected for simplicity reasons. This method allows for a high efficiency increase in the generation system, with the use of the hybridized system design by operating the generator at a higher overall load.

Auxiliary charging sources will be utilized to maximize possible power generation; this includes a variety of possible scavenged power sources, such as anything from AC wall power, 24 V FOB power, renewable resource power systems, and additional scavenged power. Renewable resource power systems include both solar inputs and wind power generation. Due to the complex nature of these systems independent circuitry is required to regulate the power before it can be utilized by the system. This circuitry for all of the auxiliary charging sources can highly vary depending on the battery chemistry chosen. Later in the paper, battery chemistries will be analyzed and an appropriate solution will be chosen, at which point circuitry adapted for this specific project will be considered.

2.3 Energy Storage

On the mobile hybridized power generation system, the quality of the energy storage has significant impact on the possible mission profiles. The energy stored, in this implementation, is used to supply power to multiple external devices, help regulate the generator output to achieve optimum efficiency, and allow the possibility of temporary silent power in stealth operations. Renewable power generation systems are currently preferred over conventional energy generation methods. However, due to their non-constant and unpredictable operating conditions, energy storage needs to be used to help meet the load at all times. [6]

An energy storage system is defined as a device or physical medium that can store energy to perform useful operation at a later period. Looking at the possible military encampments in which the HEATS system could be used, a 10 kW-hr storage system would be sufficient for most scenarios. In addition a maximum possible output of 20 kW would increase the effectiveness for high load scenarios. Energy can be stored in a variety of different solutions and technologies, ranging from mechanical storage, such as flywheels to more standard electric solutions like batteries and more. A comparison plot for multiple systems can be seen below in Figure 2-3. Many of the possible technologies can be eliminated without going into in depth analysis. Some of these technologies include all mechanical storage system, much like flywheels, compressed air storage, and pumped mass storage. With many of the energy storage technologies eliminated we are left with two possible primary technologies: standard battery packs and capacitors. Both of these technologies have been developed and refined into multiple styles.

The first, and most common method of electrical energy storage, is the use of a battery pack. A battery pack is a set of battery cells, preferably identical, that are configured in a manner to best reach required specifications. The configuration can be a mixture of both series and parallel to meet voltage and current requirements. The battery cells used in these packs are traction batteries specifically designed for high power environments. These batteries are very different from standard starting, lighting, and ignition batteries; they are designed to give power over sustained periods of time.

Batteries for this kind of scenario are characterized by their relatively high power- and energy-to-weight ratios. However, compared to liquid fuels, the current state of battery technologies has a much lower specific energy. The exact specific energy and specific power have a very wide range depending on the battery chemistry chosen. Later in the paper several different possible energy chemistries are analyzed and compared.

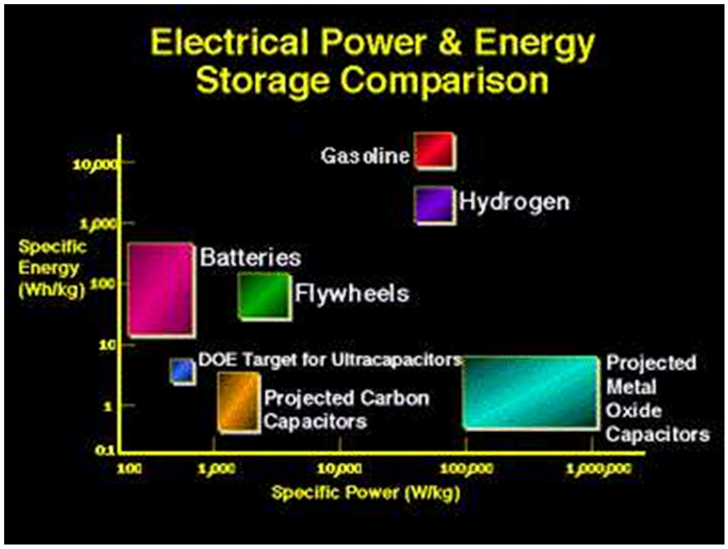


Figure 2-2: Specific Energy & Power ratings of different storage systems.[7]

In addition to the battery packs, supercapacitors, also known as ultracapacitors or electric double-layer capacitors, are also a viable method in which electrical energy can be stored. These capacitors are developed in the family of electrochemical capacitors. The double-layer capacitance works by electrostatic storage of the electrical energy obtained by the separation of charge in a Helmholtz double layer at the interface between the electrode and electrolyte. These supercapacitors fill in the gap between normal capacitors and rechargeable batteries, much like the traction batteries previously mentioned. Compared to normal capacitors, supercapacitors have a much higher energy density.

Most engineers in the field of electric vehicles can agree that ultracapacitors are the direction of energy storage for any type of electric vehicle, or hybrid electric vehicle, that everyone is moving towards.[8] Much like the earlier battery designs, the ultracapacitors seem to show a bright future for multiple additional applications at the same time. However, the ultracapacitors are still a relatively young technology that still have a significant amount of design work left.

While the ultracapacitors may be the future for energy storage, the current best technique for on-board energy storage for this application is the tried and tested battery pack. As stated earlier, there are many different types of battery chemistries that need to be analyzed; these concerns will be addressed later in the battery pack section of the design.

2.4 Power Output

There are multiple subcategories when discussing the power output of the system as a whole. First is the circuitry and conditioning required to safely supply useable power, whether it be AC or DC, to multiple loads. This is not overly complex, mostly requiring converter/inverter circuits, and a monitoring system. Most required hardware for this can be purchased as off the shelf components making from-scratch designs unnecessary. An additional, and possibly more interesting, topic to consider when designing power output systems would be managing a load prioritization and load shedding architecture. Most industrial load shedding/prioritization systems are on a very large scale, usually used by power companies.

Power systems are often designed so that in normal operating conditions there are adequate generation and transmission capacities to meet mission requirements. There are, however, limits on the excess capacity designed into a system, and at high load requirements these limits can be exceeded. There is normally a system in place to monitor power levels and reduce loading when excess load is required. The system usually senses overload conditions and sheds enough of a load to prevent any kind of permanent damage to the system. There are multiple ways to initiate the load shedding. The first is to just use a relay to sever connection with the lower priority connections to lessen the required power load onto the system. Some load shedding protocols have also been known to lower the voltage of the entire system; when this happens on the power grid it is often referred to as a brown out.

With the system being developed, the first load shedding technique will be the way excess loads are dealt with. This technique will be to simply disconnect the lower priority loads. This technique requires an in-depth monitoring system to detect high load as well as possible dangerous scenarios. In addition a control circuit will be used in tandem with solid state relays, one for each load connection. The system will be covered in depth in the design section of this paper, including possible control algorithms.

Chapter 3: Battery Pack

3.0 Chapter Summary

As previously stated, the designs will be reviewed in greater detail of all of the battery subsystems in the following sections. Seeing as how the subsystems' design directly depend on each other the chapters will be introduced in the order that most helps the reader understand the entire system. The sections that will be reviewed in this paper can be derived from the block diagram shown in Figure 3-1.

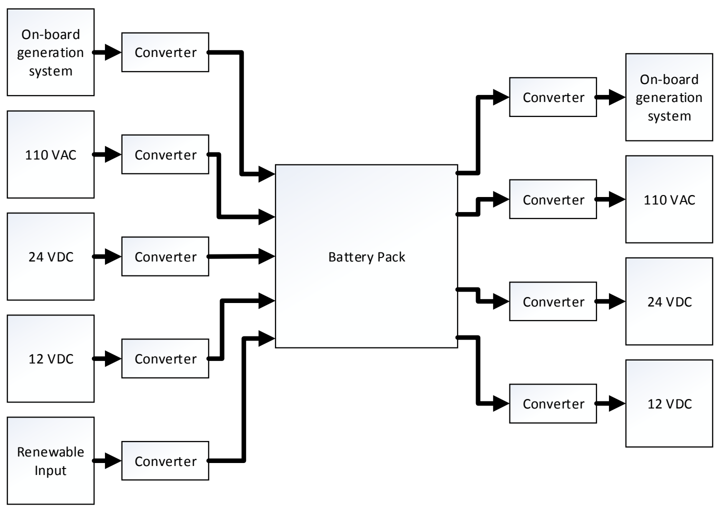


Figure 3-1: Block diagram for the basic flows of the system

Many factors need to be considered when designing a battery pack for an application such as this. Engineers have a plethora of choices in terms of the battery chemistry, size, maximum supply power, voltage, cost, and safety. The task is to prioritize the choices depending on the requirements of the project. The list of considered batteries is almost completely comprised of electric vehicle batteries, or traction batteries. These batteries differ from standard batteries, like those used in starting, lighting, and ignition in normal cars, because these batteries are designed to give larger amounts of power over sustained periods of time. Battery packs considered for electric vehicle use are characterized by the higher power-to-weight and energy-to-weight ratios. The choices have been broken up into two primary subcategories: Battery Chemistry Analysis and Battery Pack Size Calculations. In the battery chemistry analysis section the different possible battery chemistries are compared and evaluated to obtain the best choice for the application. In doing so a battery evaluation equation has been developed. In the battery pack size calculation section, the requirements developed for the problem definition were used to develop a battery pack that matches all of those needs. Multiple battery packs were developed, with a variety of voltage and amp-hour ratings, after which the most beneficial pack was chosen.

3.1 Battery Chemistry Analysis

There are a variety of different possible battery chemistries that can be used in this application. No matter what chemistry is selected, the battery pack must be able to interact, via converters and inverters, with a large variety of power applications. The implementation of this battery pack can be seen as a block diagram in Figure 3-2. This figure highlights the battery pack in the system.

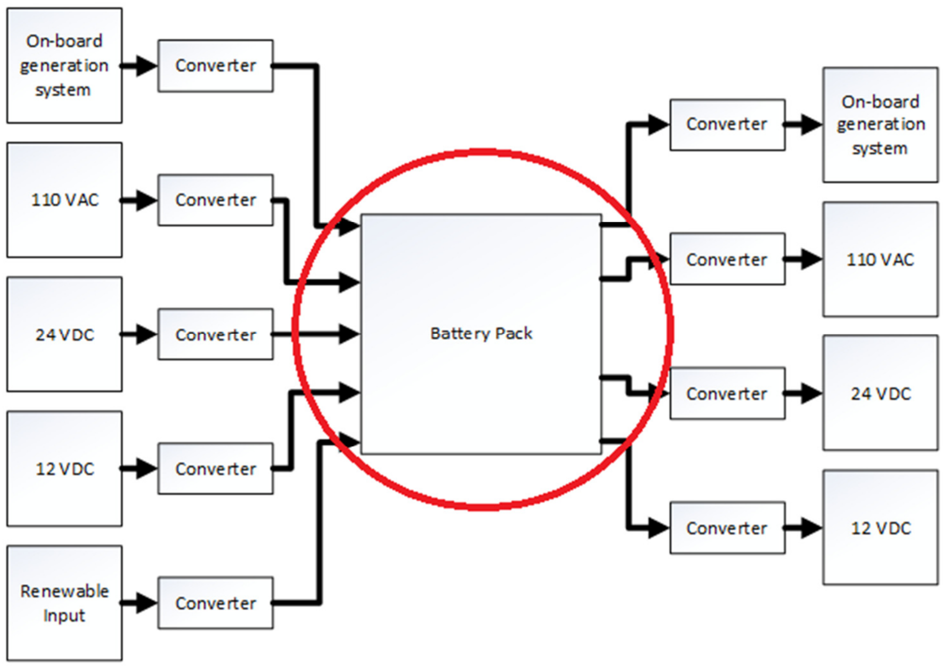


Figure 3-2: Block diagram for the basic flows highlighting energy storage.

The first battery most people think about in this scenario is also the oldest battery, a lead-acid chemistry battery. It is also the most commonly available traction battery. In this chemistry the positive electrode is made of lead oxide, the negative electrode is lead, and the entire system uses a sulfuric acid electrolyte. There are two main kinds of lead-acid batteries: starter and deep cycle batteries. The starter battery is designed for high current loads for short time spans while deep cycle batteries are for traction purposes and are more appropriate for our design. Normally, these batteries are used due to their reliability, lower cost, and higher availability. However, most systems that use a lead-acid battery pack tend to weigh significantly more. For this reason alone, almost all new projects will stay away from these batteries. Many of the battery specifications for the lead-acid battery can be seen in Table 3-1.

Table 3-1: Key information for the lead acid battery chemistry. These batteries are not very common for this kind of application.

Specific Energy	30-40	W-hr/kg
Energy Density	60-75	W-hr/l
Specific Power	180	W/kg
Cycle Durability	500-800	cycles
Nominal Cell Voltage	12	V
Key Characteristics:	Best used in stationary applications due to the high weight. Less expensive than most batteries.	

Next to be considered is the nickel-cadmium (NiCd) battery. This battery chemistry consists of a positive electrode made of nickel oxyhydroxide, the negative electrode of cadmium, and an electrolyte of potassium hydroxide. A NiCd battery has a terminal voltage of 1.2 V, which decreases only slightly until the end of the discharge cycle. This chemistry is currently made in a wide range of sizes and capacities, from small AAA batteries to batteries large enough for a vehicle energy system. These batteries are very robust and are cheaper than other batteries with similar energy ratings. They also have a long cycle life and are normally used in scenarios that require a large amount of power and extended temperature range. However, they have a lower energy density and higher memory effect than other similar batteries, which has made this chemistry less popular.

Table 3-2: Key information for the nickel-cadmium battery chemistry. These batteries are not very common for this kind of application.

Specific Energy	40-60	W-hr/kg
Energy Density	50-150	W-hr/l
Specific Power	150	W/kg
Cycle Durability	2000	cycles
Nominal Cell Voltage	1.2	v
Key Characteristics:	Highly used when high power and extended temperatures range are important.	

Nickel-metal hydride (NiMH) batteries are very similar to the nickel-cadmium batteries. These batteries use positive electrodes made of nickel oxyhydroxide like the cadmium but the negative electrodes use a hydrogen-absorbing alloy. Also similar to the nickel-cadmium, the electrolyte used is potassium hydroxide. The NiMH batteries usually have an energy density two to three times that of the cadmium chemistries. For this reason NiMH has replaced cadmium in many applications and is most widespread in smaller rechargeable batteries. This chemistry has been used on various large scale EV projects, one of the most known being the Toyota Prius battery pack.

The Toyota Prius pack, designed by Japan's Panasonic EV Energy Co., was a 38 module pack providing 273.6 V and 6.5 A-hr capacity with a weight of 118 pounds. For prolonged battery life, as well as to accept regenerative braking, the pack was normally charged between 40-60% of maximum capacity. While these batteries have good capacity and have a lower "memory effect" they have a lower cycle life and require more charge control. This chemistry is fairly popular, but has decreased in popularity as the various lithium chemistries have improved. [9]

Table 3-3: Key information for the nickel-metal hydride battery chemistry. These batteries are common for this kind of application; the image below is from a second generation Toyota Prius.

	Specific Energy	60-120	W-hr/kg
	Energy Density	140-300	W-hr/l
	Specific Power	250-1000	W/kg
	Cycle Durability	500-1000	cycles
	Nominal Cell Voltage	1.2	v
	Key Characteristics:	Have less memory effect. Used in production vehicles for the last few years.	

Lithium-ion batteries (Li-ion) are a common rechargeable battery that uses lithium ions that move from the negative electrode to the positive electrode during discharge, and back when the cell is being charged. The electrolyte in the system is an organic solvent with dissolved lithium salts. These batteries use an intercalated lithium compound as the electrode material. By using such lightweight material, this chemistry can reduce pack weight and volume by as much as 50%. This battery's self-discharge rate is also much lower than the NiMH batteries, and has virtually no memory effect. Information on this battery chemistry can be seen in Table 3-4. For these reasons this chemistry has gained real popularity among car designers, probably most known for the pure electric drive Tesla Roadster.

The Roadster battery pack is composed of 6,831 lithium ion cells arranged in 11 "blades" with each blade consisting of 9 "bricks" with each brick containing 69 cells. The fully charged system is operated at 375 V and 141.3 A-hr with a weight of 992 pounds. This system is much larger than the Prius pack, but is the only power source for the vehicle propulsion system.

While these batteries have a higher energy density with no memory effects they also require advanced protection, compared to most other battery chemistries, in order to keep voltage and current within safe operating levels. Improperly managed systems can become unstable and even reach the point of catching fire, mostly due to overvoltage issues. Due to the lack of stability in the lithium-ion chemistry, these batteries do not seem entirely appropriate for our needs.

Table 3-4: Key information for the lithium-ion battery. These batteries are fairly common for this kind of application, but are more common in smaller applications.

Specific Energy	100-265	W-hr/kg
Energy Density	250-750	W-hr/l
Specific Power	250-340	W/kg
Cycle Durability	400-800	cycles
Nominal Cell Voltage	3.7	v
Key Characteristics:	Higher density and has little to no memory effect.	

Lithium-ion Polymer (LiPo) batteries have evolved from the previously mentioned lithium-ion chemistry, where the main difference is the lithium electrolyte is not held in an organic solvent but in a solid polymer composite such as polyethylene oxide or polyacrylonitrile. They have an increased energy density, even compared to the Li-ion pack, and can be designed with a wider variety of cell sizes and shapes. The LiPo batteries are even known to have a wider margin of safety, with much higher stability in over voltage and high temperature situations. The information for this chemistry can be seen in Table 3-5.

Table 3-5: Key information for the lithium-ion polymer battery chemistry. These batteries are not very common for this kind of application, but are more common in smaller applications.

Specific Energy	260	W-hr/kg
Energy Density	540	W-hr/l
Specific Power	up to 10000	W/kg
Cycle Durability	>1000	cycles
Nominal Cell Voltage	3.7	v
Key Characteristics:	Has a premium price and requires protection circuitry.	

Most development companies agree this chemistry has very promising characteristics but that it also has a premium price tag to match, making them ideal for small personal electronics, like cell phones. With the price tag most vehicle manufactures are waiting until an improvement on the manufacturing procedures to reduce price. However, price is not the only thing to dissuade designers from this chemistry.

The final chemistry on the list to compare is the lithium iron phosphate ($LiFePO_4$) battery. This battery is considered a lithium-ion battery but uses $LiFePO_4$ as a cathode material. While this chemistry does not have as high of an energy density as other lithium ion chemistries it does have many strengths that has made it quite popular among EV applications as of late. $LiFePO_4$ tends to have an excellent cycle life, broad temperature range, a higher rate capability, and is considered the safest battery in its class. Among the most commonly available cathode materials, lithium iron phosphate is known to be one of the safest. [10] The information for this chemistry can be found in Table 3-6.

Table 3-6: Key information for the lithium-iron phosphate battery chemistry. These batteries are very common for this kind of application due to the mix and safety and performance.

	Specific Energy	108	W-hr/kg
	Energy Density	220	W-hr/l
	Specific Power	over 300	W/kg
	Cycle Durability	2000	cycles
	Nominal Cell Voltage	3.3	v
	Key Characteristics:	Excellent cycle life, high rate capability, and best in class safety.	

In addition to all of the battery specifications covered, the battery pack charge and discharge efficiencies are other crucial aspects to consider when choosing appropriate battery chemistry for any application. Most battery chemistries have fairly high charge efficiency, especially if the batteries are maintained at recommended operating conditions, mostly temperature, voltage, and current ratings. Also, depending on the chemistry, the rate at which the battery is being charged also affects the efficiency, with lower charging rates having a higher efficiency. The charging and discharging efficiencies are the physical and chemical responses to all of the different aspects of the charging process. However, an efficiency table has been constructed and displayed in Table 3-7. It is important to note that the efficiencies provided in this table are assuming a properly maintained battery pack. With the exception of NiMH chemistry most other battery chemistries have high charge and discharge efficiencies. [11]

Table 3-7: Battery charging efficiencies for each chemistry. These percentages are assuming optimal operating conditions.

Battery Chemistry	**Lead Acid**	**NiCd**	**NiMH**	**Li-Ion**	**LiFePO4**
Average (Dis)Charge Eff (%)	90-95	70-90	65-80	95-99	95-99

Choosing the appropriate battery chemistry for the project can be handled in many different ways. Additionally, the battery pack that best meets the requirements for this project may not be appropriate for other projects. For this reason, to determine the most appropriate battery chemistry a weighted decision matrix, with a corresponding battery chemistry decision equation, has been developed. This equation requires the user to rate the most important aspects of the battery pack. These ratings (V, W, X, Y, Z) add together to equal 1; the ratings chosen for this specific project can be seen in Table 3-8. The ratings used have been estimated and may not be 100% accurate, but seem to be fairly correct. For future work the values of the importance ratings can be justified or reworked. Once the importance ratings have been set, we can then compare the aspects of the battery packs to each other. The way this is accomplished is by creating a normalized value for each of the aspects by dividing each aspect by the average for all the different battery chemistries. The values used for normalization represent an "average battery" for comparison.

Table 3-8 shows the resulting decision matrix used; the higher a battery chemistry's "Average Based Rating" the more appropriate the battery chemistry is for our scenario. The table shows that the Lithium Iron Phosphate battery chemistry to be most appropriate for this project. As mentioned before, the decision matrix can be altered to the appropriate project simply by changing the importance ratings to the correct ratings for that application. From that point to calculate the new average based rating Equation 3-1 can be used. In addition, if a different battery chemistry needs to be compared, the normalization value needs to be reworked to consider the value of the new chemistry.

$$ABR_x = \left(\frac{A_x}{271.66}\right) * V + \left(\frac{B_x}{380}\right) * W + \left(\frac{C_x}{1225}\right) * X + \left(\frac{D_x}{0.583}\right) * Y + \left(\frac{E_x}{3.59}\right) * Z, \quad (3\text{-}1)$$

Where: ABR_x = Average Based Rating for given battery chemistry

A_x = Energy Density for given battery chemistry (W-hr/l)

B_x = Specific Power for given battery chemistry (W/kg)

C_x = Cycle Life for given battery chemistry (# of cycles)

D_x = Stability for given battery chemistry (unitless)

E_x = Energy/Price for given battery chemistry (W-hr/$)

V = Energy Density Importance Rating (unitless)

W = Specific Power Importance Rating (unitless)

X = Cycle Life Importance Rating (unitless)

Y = Stability Importance Rating (unitless)

Z = Energy/Price Importance Rating (unitless)

Table 3-8: Decision matrix for choosing battery chemistry. The higher the average based rating the more appropriate the battery chemistry for the scenario.

	Importance Rating	Lead Acid	Nickel-Cadmium	Nickel-Metal Hydride	Lithium Ion	Lithium-ion polymer	Lithium Iron Phosphate
Energy Density (W-hr/l)	0.15	60	100	210	500	540	220
Specific Power (W/kg)	0.2	180	150	500	300	750	400
Cycle Life (#)	0.3	500	2000	750	600	1000	2500
Stability	0.3	0.7	0.5	0.7	0.5	0.3	0.8
Energy/price (W-hr/US$)	0.05	10	2.3	2.75	2.5	1.5	2.5
Average based Rating		0.75	0.91	0.96	0.87	1.11	1.39

Using the battery selection equation it was determined that the lithium iron phosphate batteries best meet the requirements for the application. With the appropriate chemistry selected, the battery pack size design can be completed. It is important to note that manufacturer specifications are normally accurate.

Studies conducted at the University of Massachusetts Lowell have concluded that the manufacturer's specifications for both capacity and power were met on the cells tested.[12] The testing was completed on a model TS-LFP160AHA which has a nominal voltage of 3.3 V, a rating of 160 A-hr, and a weight of 5.2 kg, which results in an energy density of approximately 101.5 W-hr/kg.

Initial testing was conducted to demonstrate the capacity history over 50 complete cycles. Testing was completed on eight different cells with similar results for all. An example test can be seen below in Figure 3-3. The testing concluded that the cell does in fact have a 160 A-hr capacity as well as deliver a 90% overall efficiency, matching the specification displayed by the manufacturer. It is also good to note that, as shown here, the $LiFePO_4$ batteries do not require an "introduction" period where they must be cycled a few times before they provide full capacity, unlike a few other chemistries.

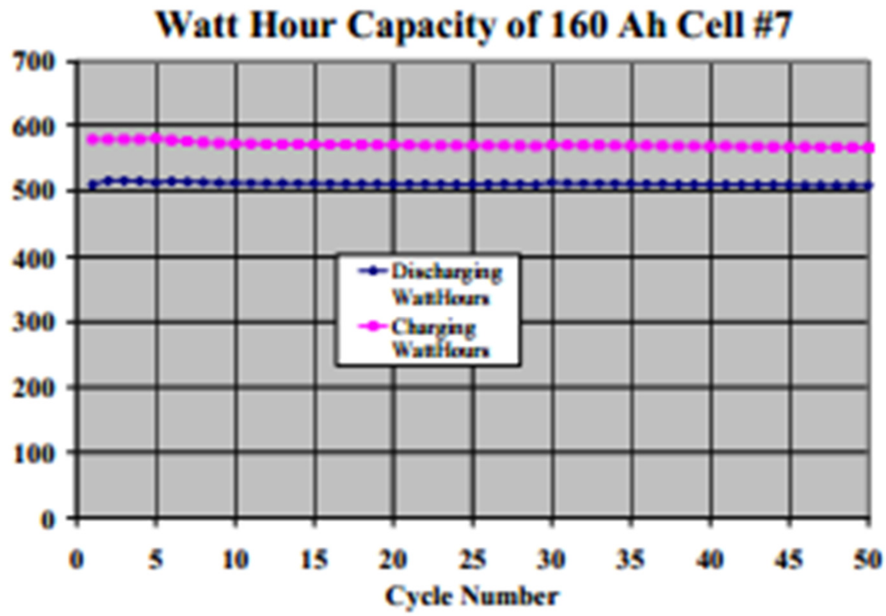


Figure 3-3: $LiFePO_4$ charge and discharge voltages. [12]

As defined in the nomenclature section of this paper, the cycle life of a battery can be defined as the number of cycles completed until the capacity of the battery reaches 80% of original specifications. The manufacturer proposed a life cycle of at least 1000 for that of the battery. In this experimentation it was found, in all the tested cells, that the capacity dropped by less than 0.5% over the course of 50 full cycles. According to the study, the trend concludes that the battery will meet the cycle life requirement. [12]

In the kind of system being designed, thermal effects of the battery pack can have large implications on the overall system. The testing showed no temperature rise inconsistent with the current flow and small internal resistance as well as no anomalous temperature change at low or high SOC. This confirms that the cells will not require unusual cooling or heating when operating in normal temperature ranges.

After determining that, theoretically, $LiFePO_4$ batteries demonstrates the best characteristics for the project, and concluding that the manufacture's batteries meet specifications the design of the battery pack can begin.

3.2 Battery Pack Design

When designing the battery system for this type of project, many steps have to be taken into account while in the development process, everything from component placement to full system integration. In the overall battery pack design, all of the issues can be divided into three different categories: mechanical, electrical, and thermal.[13] This section will aim to describe the design of the battery pack, including possible cell choices and their corresponding layouts.

So far in the battery selection process, using previously conducted research, several of the key component selection criteria have been determined including energy storage, maximum power output, and battery chemistry. However, this is only a fraction of what is required in the battery pack design. To make the rest of the selection process as easy as possible the battery from the previously mentioned testing will be used. In addition the rest of the possible battery packs will be from the same company and same line of products, just varying the capacity of the individual cells.

Designing the battery pack in this manner has resulted in four possible battery pack solutions: 160 A-hr, 100 A-hr, 50 A-hr, and 20 A-hr battery cells. [14] Each of these cell types creates highly varying battery pack characteristics. Most of these characteristics, and resulting requirements, can be seen in Table 3-9. [14] The battery packs were designed using the basic requirements established earlier in the design process. While all four of the battery pack choices meet the requirements of the system, other design aspects can be reviewed in order to make an appropriate design choice. It is also good to note that the battery pack designs were very close in overall cost among the same battery chemistry.

Table 3-9: Possible $LiFePO_4$ battery pack designs. [14]

#	Cell Voltage (V)	Nominal Capacity (A-hr)	Cell Storage (W-hr)	# of cells for 10 kW-hr	Pack Voltage (V)	Current at 20 kW (A)	Max Cont. Current (A)
1	3.2	160	512	20	64	312.50	320
2	3.2	100	320	32	102	195.31	200
3	3.2	50	160	63	202	99.21	150
4	3.2	20	64	157	502	39.81	160

#	Pulse Discharge Rate (A)	Max Charging Current (A)	Cell Weight (lbs.)	Pack Weight (lbs.)
1	350	100	12.34	246.80
2	400	100	7.71	246.72
3	300	100	4.40	277.20
4	320	80	1.80	282.60

Choice 1, using the 160A-hr battery from the research earlier in the paper, is a system made of a few larger cells. This design results in a low voltage and high current system. Having such few cells can reduce the weight of the actual battery pack by having less of the non-storage components such as casing, lugs, etc. Systems like these can be difficult to work with considering the additional hardware requirements. Having a maximum continuous current of over 300 amps requires an enormous amount of external power management as well as hardware modification. To even run wire from the battery pack would require more than 4/0 wire and very large inter-pack cell connectors. Working with wire of this caliber increases weight and cost and is a challenge for safety and ease of construction.

Choice 2, using the 100 A-hr batteries, is a better design than the previous choice 1, but still may not be the optimal design. By using additional battery cells it can be seen as a result of a higher overall pack voltage. Having this additional voltage in turn reduces current requirements lowering some of the issues from earlier. Much like the previous pack, the 100 A-hr pack also keeps the pack weight down to a minimum for this design. However, the maximum required current at 20 kW is still 195 A, requiring 3/0 wire and still uses quite large inter-cell connectors. With this battery pack many of the same issues are encountered as the previous design, just not as severe. [14]

Choice 3, using the 50 A-hr batteries, actually solves many of the issues the larger batteries have. The third choice has an even higher pack voltage providing an even lower maximum required current. With a maximum current of about 100 amps, 1 gauge wire and smaller inter-pack cell connectors can be used in the design. Using a total of 63 cells makes the battery pack layout much easier to design a more desirable layout to conform to the whole system. Also, while the battery pack itself may weigh more than both the previous choices the ability to use smaller wire and connectors will actually recover most, if not all, of the additional weight gained in this design. [14]

Choice 4, using the 20 A-hr battery, continues the trend of using smaller cells, producing a pack design with 157 cells at 502v. Having a design such as this even further lowers the maximum required amperage to fewer than 40 amps. Using this design would require 5 gauge wire and even smaller inter-pack cell connectors. Much like design 3, the requirement for a smaller hardware could make up for most, if not all, of the difference in weight. Having so many cells means that they could arranged in a number of ways, depending on the overall design. However, having a voltage over 500 V makes safety concerns very problematic. The design also makes system monitoring more difficult. [14]

After reviewing all four of the possible battery designs, it has been determined that choice number 3 is most likely the best design. The 50 A-hr battery cell meets a happy medium for voltage, external hardware, space, safety issues, and the other concerns. Also, looking into maximum and continuous charge and discharge currents, this battery set seems to give a relatively large factor of safety while keeping the overall system fairly organized. The specifications for the selected battery can be seen in Table 3-10 below. Now that the battery cell type has been selected, external hardware required for the pack design can be reviewed.

In this chapter, when referred to battery pack external hardware refers to appropriate connectors, wire, containment, etc.; this does not include electric components like contactors and circuitry, they will be covered in later sections. For this system copper bus bar can be used for the inter-pack connections and, as said before, 1 gauge wire can be used on both sides of the battery pack.

Table 3-10: Chosen battery cell information. Image of the selected battery (left) and the matching specifications (right). [14]

Specification	Value
Nominal Voltage:	3.2v
Nominal Capacity:	50Ah
Internal Resistance:	<1.5mΩ
Discharge Protecting Voltage:	2.3v
Charge Protecting Voltage	3.7 +/- 5V
Max. Continuous Discharge:	3C (150A)
Pulse Discharge Rate:	6C (300A, 10s)
Max. Charging Current:	2C (100A)
Pulse Charging Current:	3C (150A, 10s)
Weight:	2000g
Dimensions:	30x201x171mm
Cycle Life at 80%:	1500 cycles
Lead Time:	50 +/-10 days

3.3 Battery Pack Management System

The objective of this section is to demonstrate a design for a per-cell management system for the $LiFePO_4$ battery pack. In order to construct an effective management system many conditions need to be considered, such as high temperature, high current, over charging, over discharging, unbalanced cells, and additional safety systems. To take all of the conditions into consideration, multiple sections have been included. The first of which is the cell characterization section. This section describes how to identify battery characteristics required for a proper management system to enhance the functionality of the overall management system. The second section is the state of charge tracking and system protection design. This section describes how state of charge tracking is handled and the corresponding basic circuitry that accompanies the design. The third section in this chapter reviews cell balancing, notably why it is important and how it can be implemented. For the system a passive cell balancing technique was chosen. The final section of this chapter reviews the entire system integration and how all the different components interact with each other. Additionally, the system needs to be able to visually demonstrate the functionality of the design in communicating status updates. A basic flow chart of the battery management system, or BMS, can be seen in Figure 3-4. This figure shows how the state of health is determined where the battery characteristics information is determined from the cell characterization on determining state of charge with outside environmental effects.

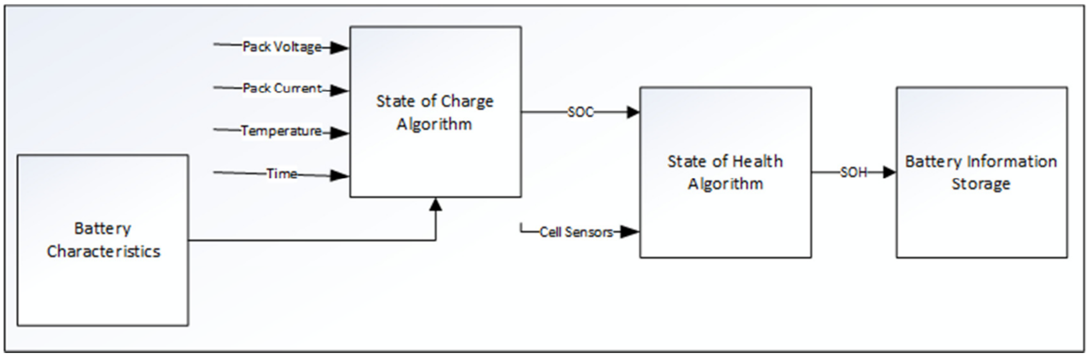


Figure 3-4: Generalized flow chart for the battery management system. This system is covered more in-depth later in the paper.

3.3.1 Cell Characterization

Before the management system can be designed both cell balancing and state of charge, SOC, estimation must be developed. The techniques used for these systems must understand the $LiFePO_4$ cells within the system. Tests can be performed in order to obtain the charge and discharge characteristics of the cells. For instance, testing would reveal that the battery SOC is not linear with the battery voltage but resembles Figure 3-5. The plot below is a SOC plot for a $LiFePO_4$ battery and does not exactly reflect the battery chosen, however it should be very close. Due to this fact the SOC algorithm cannot be designed solely on the pack voltage but rather the voltage thresholds, coulomb counting, and timing. Continued work would involve characterizing the individual cell chosen.

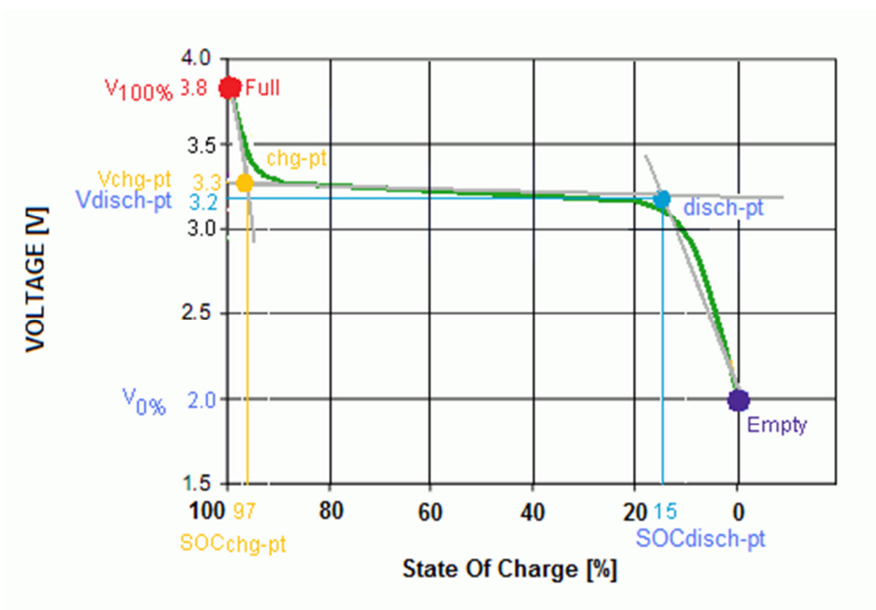


Figure 3-5: State of charge relative to voltage for $LiFePO_4$. [15]

3.3.2 State of Charge Estimation and System Protection

State of charge is the battery pack equivalent of a standard vehicle or generator fuel gauge. SOC is usually expressed as a percentage, where 0% is empty and 100% is full. This can provide valuable information to determine how much longer the system will continue to provide power before recharging is required. The SOC can be calculated with either the max charge capacity or the original rated capacity. For this project the original rated capacity will be used due to the fact that batteries degrade as time goes on, and this gives a more representative reading of the energy remaining. This means towards the end of the battery pack's life, 80% original capacity, a topped off battery pack would only read 80% rather than the 100%. It is good to note that either technique would be satisfactory for cell balancing techniques, considering it is only required that the SOC of any cell is relative to the other cells in the pack.

SOC usually cannot be determined directly, but in general there are a few common methods to determine SOC. There is a chemical method in which specific gravity of the electrolyte can be used to indicate SOC. This only works with batteries that offer access to their liquid electrolyte, so this method cannot be used with this project. A possibly viable method is known as the voltage method, which entails simply reading the battery voltage and comparing the current voltage to the known SOC versus voltage plot. Cell voltage characteristics alone are less useful for determining state of charge for multiple reasons. Firstly, the cell voltage is nearly constant over much of the charge range, making pinpointing SOC a challenge. Additionally, hysteresis makes this technique increasingly difficult, due to the open circuit voltage (OCV) after a charge is higher than the OCV after a discharge, or even after rest. This is due to the time constant associated with the delay in the battery's reaction in keeping up with the electrical stimulus. The SOC calculation in this method varies with temperature, current, and voltage across the cells. With all of these factors, an extensive look-up table would be required for all the different scenarios. [16]

A third method for state of charge estimation is current integration, or "coulomb counting," which is a fairly common and viable method for projects similar to this. The energy in an electric charge is measured in coulombs which is equal to the integral over time of the current that provided the charge. You can calculate SOC in this method by measuring the current charging and current depleting from the battery and integrating the results over time. Another way of saying this is that the charge transferred into or out of the pack is obtained by summing the difference in current over time. Equation 3-2 below represents this technique and how to solve for current SOC, having already known previous SOC and characterized the battery.

$$SOC = SOC_0 + \frac{\int \eta * I dt}{C}, \qquad (3\text{-}2)$$

Where: SOC = Current state of charge
SOC_0 = State of charge @ t-1
η = Tested charge/discharge battery efficiency
I = Average current charge/discharge for that time step
C = Temperature/Current factor

This technique also has a couple of known issues. The SOC starting point must be known before integration, also that this method can suffer long term from small errors. With long-term error drift and a lack for a reference point recalibration is required regularly, with the calibration point normally being a fully charged pack.

A key aspect of this method is the ability to accurately measure the current into or out of the pack. In this method, current is usually obtained using one of three methods. First is a current shunt which is the simplest method. It works by measuring the voltage drop across a low value resistor between the battery and the load. This method causes a slight power loss and heats up the battery slightly. Second, a hall effect transducer can be used. It would eliminate both power loss and the temperature increase. However, most cannot tolerate extremely high currents and can be susceptible to noise. Lastly, a GMR sensor could be used due to the higher sensitivity, signal level, and temperature stability. These sensors are known to be fairly expensive and harder to work with.

In this project a mixture of both the current integration and voltage SOC estimation techniques will be implemented into the design. As stated earlier, current integration can be used to determine the change in SOC. A reference point must first be established. At this point the voltage method will be used to determine SOC. $LiFePO_4$ batteries can be considered "steady state," hysteresis unaffected, after approximately 6 hours. [17] Before a long-term use of the generators, the system will rest for approximately 6 hours and then use a simplified lookup table to determine the starting state of charge for the system. How often this calibrating would be required would depend on the accuracy of the current integration. Extensive testing is necessary to more accurately determine how often this phase of SOC estimation would be required. With a valid SOC starting point an accurate method to complete the current integration is then required.

Many companies have started to create useful tools to make this method easier to implement. One company developing such tools to help accomplish this goal is Texas Instruments. They have developed several "fuel gauge solutions" that perform current integration with impedance tracking specifically designed for Li-ion and $LiFePO_4$ battery chemistries. One chip that has been selected is the BQ34Z100, the "Wide Range Fuel Gauge with Impedance Track^{TM} Technology (rev. B); an image of this chip can be seen in Figure 3-6. The BQ34Z100 is known to be able to accurately predict the battery capacity and additional characteristics of a single cell of multiple rechargeable cell blocks. This system can communicate with a host processor to provide valuable pack information including remaining capacity, full charge capacity, and average current.

Figure 3-6: Texas Instruments chip for current integration.

While slightly out of the scope of this report, it is important to note how the Texas Instruments solution will be implemented in the system. In Figure 3-7, the typical implementation that has been provided in the documentation for the chip can be seen. While not going into great detail about the design of the circuit, the basic operations of the chip are very important and influence the overall design. Also, it is noteworthy that the "Protection and Balancing Solutions" recommended in this circuitry is designed to balance the pack at 100-150 mA. [18] Using this chip would take 10 hours to balance an offset of 1Ah. Because of this, cell balances will be dealt with separately in the upcoming cell balancing section.

To access the information on the system a series of commands is required, whether it is the standard commands or the extended commands, to access further capabilities. Both command sets are used to read and write information obtained by the chip and can be sent via multiple communication engines, including I^2C. [18] The information is then stored in non-volatile flash memory while also providing 32 bytes of user-programmable data flash memory. [18]

This manufacturer claims to have extremely high accuracy, claiming as little as 1% error across a wide variety of operating conditions. The system measures the charge current and discharge current by monitoring a very low value shunt resistor, labeled Sense Resistor in Figure 3-7, that is connected on the ground side of the battery. When the system is under load, the cell impedance is measured by using the OCV with the measured voltage under loading conditions.

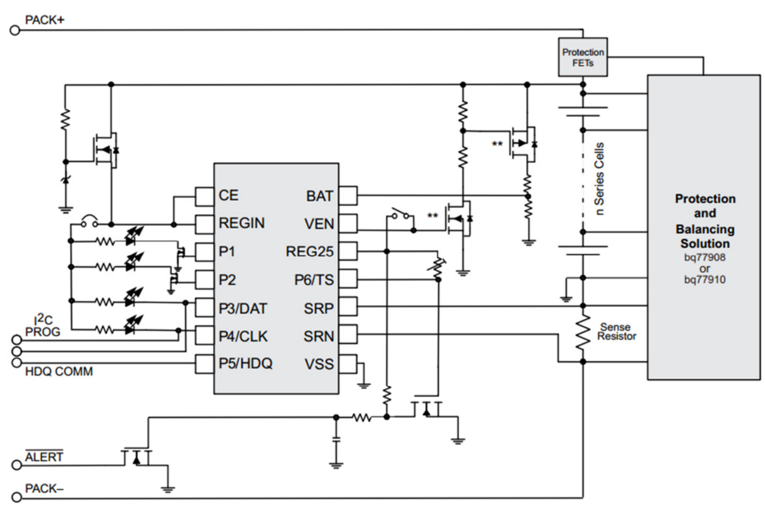


Figure 3-7: Circuit diagram for current integration chip. It is worth taking note that the "Balancing Solutions" do not fit our project specifications, so will be dealt with separately. [18]

As can be seen in Figure 3-7, a protection solution is required to be implemented alongside of the state of charge estimation and cell balancing requirements. For this, the suggested chip by Texas Instruments has been selected for the system, the BQ77910 precision protector, an image of which can be seen in Figure 3-8. The BQ77910 chip is described as a complete stand-alone, self-contained battery-protection and cell-balancing device intended for Li-ion/polymer battery packs. As stated earlier, the balancing function will not be used on this chip, due to the extended time required for complete balancing. This chip monitors up anywhere from 4 to 10 series individual cell voltages and can be used to quickly drive MOSFETs to interrupt the power path to prevent permanent damage to the overall system. However, the proposed design would require 7 of these chips for full system monitoring, this also means that 7 of the state of charge estimation chips are required as well. The chip is fully programmable in the memory, where activation delays and recovery methods for each safety condition can be fully programmed.

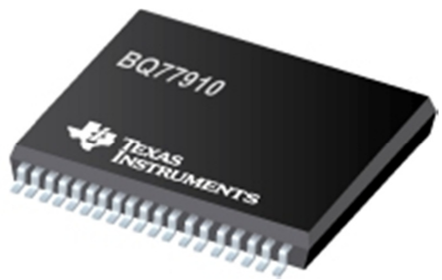


Figure 3-8: Texas Instrument Chip recommended for battery pack protection. [18]

As mentioned earlier, the BQ77910 chip has a wide range of programmable protection functions built into the system. Using this chip, a wide range of programmable detection thresholds and delay times are available to find one that best fits the system. Additionally, there is the ability to configure the system for multiple cell types and application requirements. The user has the option to program into the system protection functions regarding any of the following: cell over voltage, cell under voltage, pack discharge over current, pack discharge short circuit, and pack charge short circuit. The chip also has a variable gain, x1 to x5, current senser circuit compatible with a large variety of current sensor resistors, typically in the 1 mΩ to 5 mΩ range depending on the application requirement. In addition to the programmable protection functions, this chip has several fixed hardware protection functions. [18] These functions include preset over temperature protections, open cell detection, open and shorted thermistor detection, and brownout protection that can quickly shut off FETs under low-battery conditions to avoid FET overheating.

3.3.3 Cell Balancing

Cell balancing and energy redistribution are techniques that are designed to maximize a battery pack's capacity to make more energy available to be used as well as increase the overall lifetime of the battery. Battery balancers can be found in smaller applications, such as cell phones and laptops, but are almost certainly in most high quality electric vehicle battery packs. Usually, individual cells in a battery pack can have slightly different capacities. Additionally, resistances may even start with different states of charge. Obtaining batteries from the same lot can help to reduce these effects. If the cells are not balanced the battery pack can only supply power until the cell with the lowest available capacity is at the cutoff voltage, even if the other cells still contain useable energy. This makes the cell with the lowest capacity a “weak link” in the system. Continuing to operate the system in these conditions can lead to overcharged or over-discharged cells, possibly causing permanent damage, while other cells are seeing partial load. Figure 3-9 demonstrates how an unbalanced pack could be affected. It can be seen how cell four would be damaged after multiple cycles and what little amount of battery can actually be used in this scenario. The balancer prevents this from happening and helps to protect the lower capacity cells. Once the battery pack has been balanced there is no weak link in the system. This prevents individual cell damage being caused by unbalanced cell overcharging.

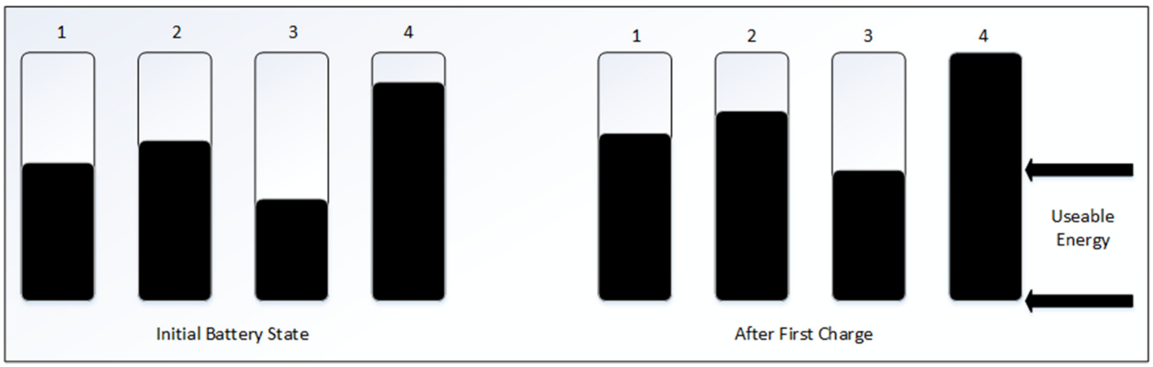


Figure 3-9: Importance of cell balancing. Unbalanced Cells, cycling a pack in this nature will cause permanent damage to the higher cells, ass seen in cell 4 in this figure.

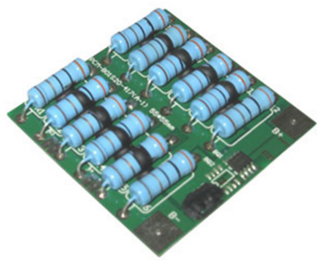
There are primarily two different techniques used to balance all of the cells in a battery pack. Battery balancing can be completed using either passive or active cell balancing techniques. [19] Passive balancing is the easiest approach to cell balancing using a dissipative technique to equalize voltage and is used in smaller applications such as power tools, uninterruptible power supplies, medical equipment, and even some power-assisted bicycles and scooters. This is completed by finding the cells with the highest voltage in the pack and removing extra energy, usually through a bypass resistor until the voltage matches that of the lower cells. Many passive systems stop primary charging when the highest charged cell is at 100% SOC. [19] They then discharge the higher charged cells until they reach the level of the lower charged cells. The basis of this technique is to level down, which can create unnecessary losses, as well as heat, in the system. Also because this technique uses low bypass currents the equalization process can take a long time.

Alternately, active cell balancing uses capacitive or inductive charging to be able to deliver energy from the highest cell to the lowest cell, with little loss in the process. [19] This technique is usually preferable for efficiency-based designs due to overcoming the energy loss that the passive technique creates. With independent charging of all the cells simultaneously nearly impossible, usually the balancing charge must be applied to the active cells individually, creating very long balancing times. Within active balancing there are two primary techniques to redistribute charge throughout the system. [19] The first method is referred to as the charge shuttle, or flying capacitor, charge distribution. In this technique a capacitor is switched sequentially across each cell in the series, averaging the charge level on the cells by removing charge from higher cells and placing charge into the lower cells. This process can be optimized by programmatically taking charge from the highest cell and placing it in the lowest charged cell. This technique can be fairly complex, depending on the cell count, require expensive electronics, and reach lower efficiency as the voltage difference is reduced. The second technique is the inductive shuttle charge distribution method. This technique uses a transformer with its primary winding connected across a battery and the secondary winding that can be switched to interface with individual cells in the system. It charges the cell using energy from an external battery rather than from individual cells. In doing so this technique averages the charge level, as did the previous technique, but helps to avoid the issue of small voltage differences, affecting efficiency, and resulting in possibly faster balancing times. This system requires balanced secondary transformer windings; otherwise it could just compound the problem.

Knowing the information above about the various types of cell balancing systems and the projected use of the system, a passive method of balancing has been selected, draining the higher energy cells to a more desirable system level. This method sacrifices a small amount of efficiency, and added heat generation, in favor of a simpler, cheaper, and faster method. Due to the nature of the $LiFePO_4$ battery chemistry, cells have the highest danger of becoming out of line at very high loads, at the range of 5C, much higher than the maximum proposed current output for the system. [20] Due to the nature of the chosen battery chemistry, the system balancing should not be required often. With balancing being a rare occurrence, the energy loss due to the efficiency difference will be negligible, and worth sacrificing to implement a simpler solution for both design and any kind of required future repairs or modifications.

Much like the monitoring equipment, balancing equipment is becoming much more popular as HEVs become more popular. Because of this we have the ability to purchase off the shelf components for issues like this. Due to everything mentioned above, the cell balance module developed by AA Portable Power Corp has been selected. The design specification information can be seen in Table 3-11, PCM-B01S20-4176(A-1) smart balance module.[21] This module has been chosen due to the high variability of operation parameters capable. This module operates by keeping each of the $LiFePO_4$ cell's voltage at 3.60V peak during charging by draining excessive voltage with a selectable, from 0.65A to 1.44A, discharge current. The system waits for all of the cells in the pack to reach the same voltage level to verify that all cells within the pack are balanced. By adding the module on each of the battery cells before constructing the battery pack the users will be able to increase cycle life, maintain battery power throughout the life of the batteries, as well as save money long term on the overall pack. The balance boards communicate with one another to determine the level they are working towards. An example of how the balance modules are to be implemented into the system can be seen in Figure 3-10.

Table 3-11: Specifications for the balance module proposed for the system.



Test Item		
Specification	Specification Parameter	Criterion
Voltage	Cell-balance Detection Voltage	3.600±0.025V
	Cell-balance Release Voltage	3.500±0.050V
	Cell-balance Detection Delay Time	0.96 - 1.4s
Current	Balance current 1 / Balance current 2	0.65mA/0.9mA
	Balance current 3 / Balance current 4	1.1A/1.4A
	Current Consumption During Operation	<20µA
Temperature	Operating Ambient Temperature	-40 to +125 C
	Storage Temperature	-55 to + 125 C
	Continuous Balance Resistance Temperature	≤ 85 C

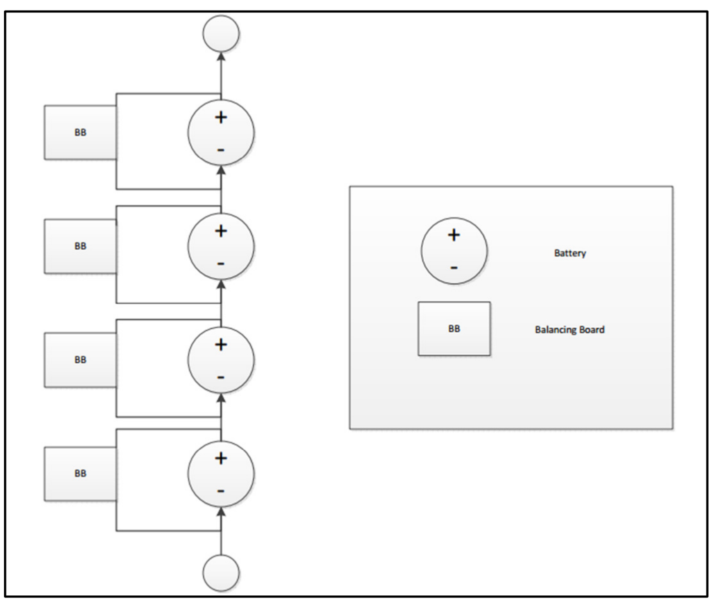


Figure 3-10: Battery balance board setup. Generalized diagram on how the balance module is going to be implemented into the overall battery pack, and how the boards interact with the individual cells.

3.3.4 Battery Management System Integration

A battery management system is defined as any electronic system that manages a rechargeable battery pack, such as by monitoring its state, calculating secondary data, reporting that data, protecting the battery, controlling its environment, and/or balancing the system. Using numerous battery management systems, the system information is fed to various controllers to optimize battery life and assure long term safe operation. While the in-depth system integration is beyond the scope of this report, how the systems interact with each other on a larger scale can be reviewed.

The battery management system to be implemented in this scenario consists of multiple subsystems, reviewed earlier, working together to determine the overall health and state of the battery pack. These subsystems include state of charge calculation, system protection, and cell balancing. Determining the state of the battery at each individual cell in the pack must be taken into consideration. Figure 3-11 shows how the information is obtained. In the figure, the circuits already discussed have been simplified to simple block representations. Figure 3-11, the Isolated DAQ Subset, is a generalized diagram, but holds true to our design. There are several things to note about the design in respect to our system. First, the system can monitor a maximum number of cells, depending on each of the subsystems. For our case, the limiting factor is the protection board, which can monitor up to 10 battery cells at any one time. Additionally, it is important to note that the line running to the negative terminal of the power isolator originates at the lowest voltage point of the battery cell subset, creating a floating ground for the system.

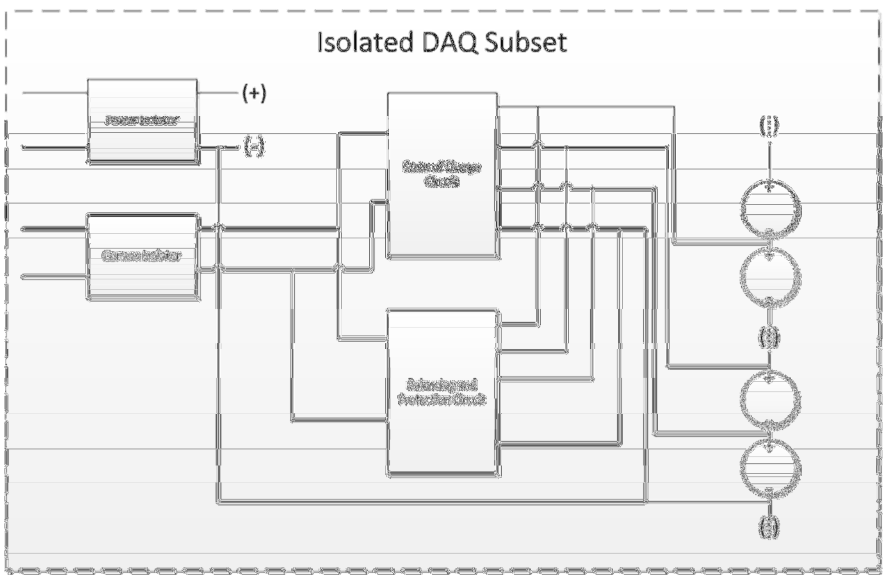


Figure 3-11: Isolated DAQ subset. Generalized diagram that displays how the battery pack information is obtained. With the chip selected, up to 10 battery cells can be monitored in the Isolated Data Acquisition system.

The way that this information is recorded, processed, and acted upon can be seen in Figure 3-12. The isolated DAQ subset, just previously discussed, can be seen on the left side of the figure. Much like the last figure, this is also a generalized system that holds true in regards to several different systems as well as circuits used. Much like the number of battery cells from the previous figure, the number of isolated DAQ subsets can vary depending on the system needs and requirements. For our specific system, 7 of the isolated DAQ subsets will be required, considering each subset monitors 10 batteries and the battery pack designed has 63 individual cells. It is important to note, in both Figures 3-11 and 3-12, there are numerous isolators in the system. This is to prevent any of the management system boards from being damaged by excessive voltage. The entire data collection can then be communicated to a "Master" micro controller. I^2C style communication is recommended for this design. The data can then be analyzed to determine the overall health and status of the battery pack as well as shared to any other subsystems or external monitoring systems via an Ethernet connection. Ethernet is an isolated communication circuit; adding an additional isolator to the micro controller power supply provides two layers of isolation from the battery pack.

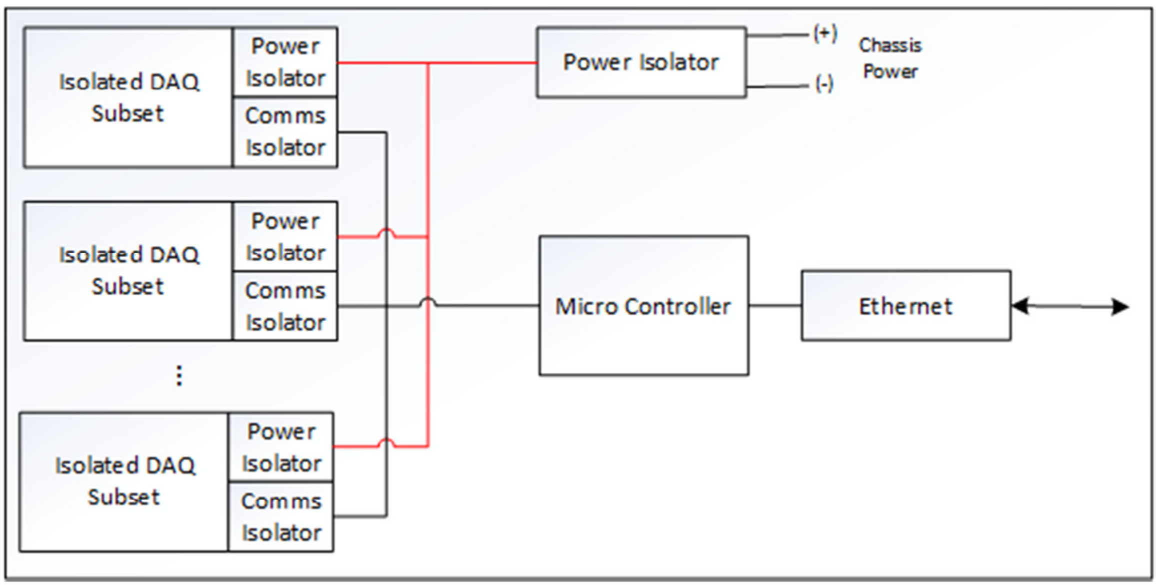


Figure 3-12: Isolated DAQ subsets processed and monitored. Note that the number of Isolated DAQ subsets can range depending on the battery pack cell size.

As stated before this is a big picture look at the management system integration and additional information would be required in a final design. Some of the required information includes the kind of isolators required (1-way vs. 2-way), the "Master" micro controller design, the communication packet design, etc. However, the proposed system above would meet all of the requirements necessary for a system such as this.

Chapter 4: Power Input

4.0 Chapter Summary

The objective of this chapter is to demonstrate a design to manage a variety of different charging loads into the $LiFePO_4$ battery pack. Figure 4-1 shows how power input relates to the rest of the system. In order to design an efficient, as well as safe, system, many different conditions and sources need to be considered in the overall design. Some of these conditions include on-board generated power, renewable resource power, variety of scavenged power sources, and a method of managing all of the power inputs into the system. However, before any of these conditions are considered, first an efficient charging strategy that will help determine the kind of control strategy to be used in the system needs to be developed. Additionally, simulations have been constructed to show the increased efficiencies gained from the hybridized system over the standard generation system.

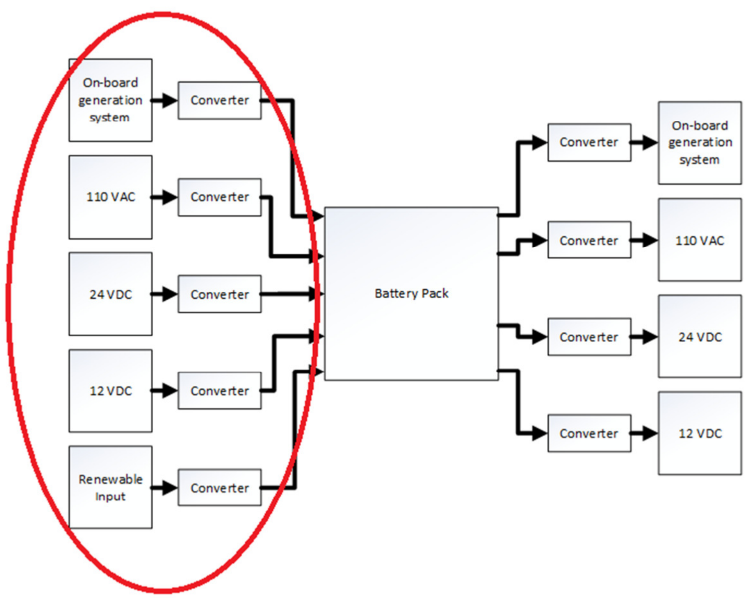


Figure 4-1: Block diagram for the basic flows highlighting power input.

4.1 Battery Charging Strategy

Developing a lithium battery charging strategy is a key factor to ensure safe and reliable operation of the entire system. A battery charger has three key functions it needs to be able to accomplish. These tasks will be taken care of between the charging strategy and the battery management system. The first key function is simply charging, or getting the charge generated or obtained from outside sources into the battery pack. The second key function is stabilizing the charging system by optimizing the charging rate and method into the battery pack. The third, and final, function is terminating the charge, knowing when to safely stop the charging process. A charging scheme is simply the combination of the charging and termination methods.

Overcharging a battery is a high risk that can be caused by a number of different sources: errors in determining the cutoff point, cell abuse cause by rise in temperature, and internal fault conditions within the battery. Once a battery pack is fully charged, the current used for charging is required to be dissipated in some way. Overcharging a battery pack normally results in the generation of heat and gasses, both of which are harmful for batteries and can easily cause long term damage to the system. The backbone to quality charging is to have the ability to detect how far along the charge process is and to manipulate the system as needed, whether it is to stop charging or change the charging technique. In addition to overcharging, with the use of a fast charging system, it is possible to supply more electrical power into the battery faster than the battery can chemically process it, leading to damaged cells. To prevent any of the previously mentioned damage there are several basic charging methods commonly used with battery packs in most applications.

There are quite a few possible charging methods that can be implemented into our system; this section will review several of these methods and determine the most appropriate for the given scenario. The first, and probably the simplest, method of charging is known as Constant Voltage. A charger that operates off of the principle of constant voltage is essentially a DC power supply, which could simply be a step down transformer from the main source with a rectifier to provide the voltage for the system. This technique is often used for car battery chargers by cheaper systems and is mostly used with lead-acid cells. However, the general technique is used fairly often with lithium-ion cells alongside additional circuitry to provide overall safety in the system. Another charging method often used is a constant current style charger which just varies the voltage applied to the battery pack in order to maintain a constant current flow. The system then switches off when the voltage reaches a required level of charge; this system is normally used for charging battery systems to a mostly-charged state. Operating in this method ensures damage is not caused to the battery by overcharge.

Another basic charging method often used is a pulsed charge system which delivers the charge power to the battery in pulses. The rate of charge required can be accurately controlled by varying the width of the pulses, which normally runs for approximately one second intervals. While in the charging process, shorter "rest" times are used between the pulses, normally around 20 to 30 milliseconds, to allow the battery to chemically stabilize. With this technique it is possible to probe the open circuit voltage during the rest periods. Note that the open circuit voltage would not be the settled voltage. In addition to pulse charging, there is also a negative pulse charging, also known as burp charging or reflex charging. This technique is a modification of pulse charging, applying a short discharge pulse, normally around 2 times larger than the charging current for as little as 5 milliseconds. What this does is dislodge any gas bubbles that may have built up around the electrodes during fast charging which in turn increases the stabilization and the overall charging process. The last technique to be reviewed is the float charge method, where the battery and the associate load are permanently connected in parallel with a DC power supply being held at a constant voltage, below the battery pack's upper voltage limit. However, this technique is not very popular for our application, and it will mostly be used in emergency power back up system using lead acid battery packs.

Many of the charge methods previously mentioned are not, by themselves, an adequate solution to the system that is being worked with. However, using a combination of constant current then constant voltage is a very common method of charging most lithium chemistry battery packs, as well as a variety of other batteries that are more vulnerable to damage if the upper voltage limit is exceeded. All batteries have a manufacturer's specified maximum constant current charging rate which indicates the maximum input the battery can withstand without damaging the battery cells. By charging the system constant current to start the input into the battery system can be maximized using a fast charge scheme. When the battery pack reaches a given state of charge special precautions are then implemented to ensure that the battery reaches full charge while at the same time avoiding damaging the system by overcharging. That is why the system then switches to a constant voltage under the upper limit of the battery. Figure 4-2 shows the battery pack properties during a constant current then constant voltage charging method.[22] Note that the red line in the image shows the point at which the charging scheme transitions from constant current to voltage.

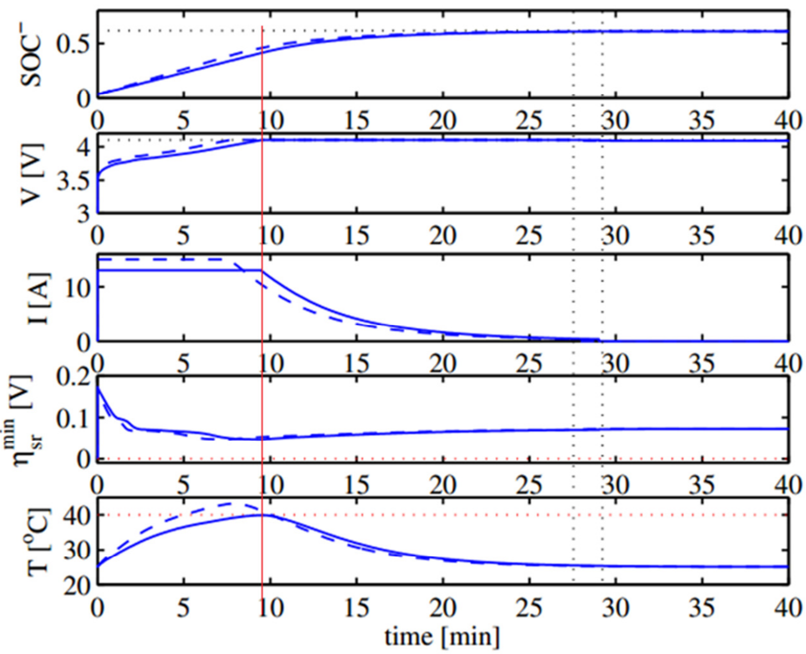


Figure 4-2: Battery pack behavior during a CCCV charge method. This image shows two slightly different schemes. Note that the red line is where the system changes from constant current to constant voltage.[22]

Most lithium based cells charge to 3.8 volts for each cell in the pack, charging to an increased voltage would increase the capacity but at cost of the service life of the pack. Given that information, the normal current input into a battery cell, during the constant current stage of the battery cycle, ranges from 0.5C to 1C. [22] Note that maximum continuous charge current for the battery selected is 2C, with a pulse as high as 3C, but for efficiency reasons most manufacturers recommend charging the cells at 0.9C or less. Charging at a lower input allows for possible efficiencies around 97 to 99% and the cells remain cooler during the charge; however, most packs see a temperature rise by a few degrees.[23] In Figure 4-3, the flowchart describes the constant current constant voltage charging method, as well as the points at which the system would check for safety precautions and transition points.

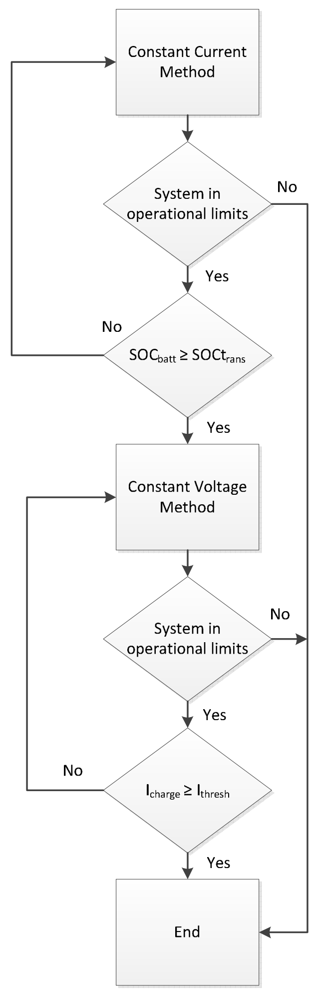


Figure 4-3: Flowchart of CCCV charging scheme.

Increasing the charge power into the battery cells does not reduce the full charge time significantly, but it does cause the battery to reach the peak switch voltage sooner causing a shorter constant current stage, but the constant voltage section of the charge will take significantly longer. Given this, the battery pack can be fast charged reliably to approximately 80% maximum charge each cycle. The battery pack as a whole does not require being fully charged to be operable. Considering that exceeding the maximum voltage can cause permanent damage to the cell, many developers lower the voltage threshold slightly on one or both stages of the charge. When the battery pack has initially begun charging, the pack voltage shoots up quite dramatically in the beginning. However, the voltage of the battery pack, while being charged, will catch up towards the end of the charging cycle. For this reason the capacity of the pack cannot be read simply using the closed circuit voltage, and why it has been decided to estimate battery state of charge with the previously mentioned hardware and measuring open circuit voltage once the battery pack has reached a steady state after resting for up to 6 hours, while also taking outside considerations into effect, such as cell temperature.

The lithium battery pack proposed cannot absorb additional charge past recommended capacity limitations; once the system is fully charged the current into the system must be terminated. If current is not removed, even if just a small amount of current remains, it could cause plating of metallic lithium causing permanent cell damage and safety issues. To reduce the overall stress the cells see, it is recommended that lithium-based packs remain at 3.8 V/cell, the maximum charge voltage, for as little time as possible to extend battery life. After the charging source is stopped, the pack voltage starts to drop, lowering the stress caused by the higher voltage status. After some time, the open circuit voltage will rest somewhere in the range of 3.6 and 3.7 V/cell. The time it takes to meet the previously mentioned range is determined by the amount of time the system has been allowed to charge at the constant voltage charging scheme, the longer it is charged like this the longer it takes the system to settle.

If the mission operating conditions require the additional battery storage, pack voltage closer to 3.8 V/cell rather than 3.6 V/cell a lower-powered charging scheme can be used as a "top off" charge to compensate for the self-discharge of the battery cells and the corresponding protective circuits. Many charging schemes are designed to top off the battery pack if the overall system reaches a reading as low as 3.7 V/cell, and turn off again once 3.8 V/cell is reached, this technique tends to stress the battery cells slightly. Other "top off" schemes will charge the battery pack when the cells reach an open circuit voltage of 3.6 V/cell but only charge to 3.7 V/cell, rather than the original 3.8 V/cell, reducing stress from the battery pack resulting in a longer battery life. [21]

Many battery experts have agreed that developing lithium-based battery charging schemes, and chargers, are much less difficult than designing other style battery charging schemes, including nickel-based systems.[24] Not only is determining the criteria for the different stages of charging more simple, but the required charge circuits are relatively simple as well. Most other systems require analyzing complex signatures of the battery status, which usually have a tendency to vary with age. In addition, this charging technique, along with the battery chemistry selected, is much less critical on the kind of charge that can be used; from high power production, much like our on-board generator sets, to low intermittent charging, similar to the renewable energy discussed later in the paper, without causing any negative side effects to the battery pack system.

4.2 Mobile On-Board Generation System

The use of mobile power generation systems is a concept that has been widely adopted with use both in a military setting and by the public. They come in a wide range of sizes anywhere from 1 kW to 200 kW. Mobile generators are a common site on any forward operating base, as energy is always a precious item on today's front lines. The 10 kW diesel generators being used as the HEATS vehicle's primary method of energy generation are very similar to the generators currently being used every day for mobile power requirement scenarios. To understand how a hybridized generation system can be used to reduce fuel, it is important to understand the general operations of a generator set.

A generator set can be, to simplify, thought of as an internal combustion engine in conjunction with an in-line alternator. The engine uses both fuel and air in order to cause combustion inside the cylinders of the engine, the resulting expansion of fuel runs a crank shaft connected to the output shaft of the engine. With the engine output, being connected to the alternator input creates electrical energy to meet load requirements.

The energy conversion from liquid fuel to electrical energy, from a thermodynamic standpoint, is not an efficient system. Efficiencies are from 5-45%, depending primarily on the load profile of the system. Having such a low fraction of possible total energy to start with, it is important that the output of the system is maximized. Figure 4-4, below, shows an example for an engine efficiency map where the rings indicate different efficiency profiles.

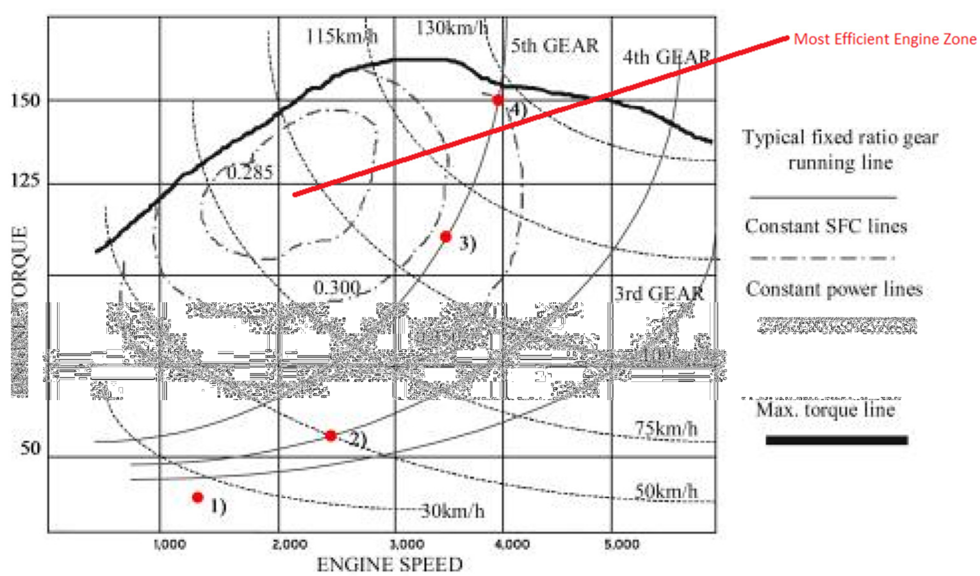


Figure 4-4: Efficiency plot of an engine. The most efficient area in the cycle has been labeled.[25]

This maps displays the fuel required to operate at a given RPM and torque, with the darker edge line displaying the maximum torque the engine can output at a given RPM. Each of the "zones" in the plot shows a respective efficiency range, with the most efficient zone identified by the red line. The generator wants to operate in this zone as much as possible, as long as the power requirements do not exceed the system's parameters for the more efficient zones. Every engine is slightly different; the figure is an approximation to what a diesel generator engine could look like.

Most engines operate with the ability to change gearing ratios in the system, using a multi-gear drivetrain, so it is possible to try to change the RPM and torque ratios to obtain a more efficient cycle. Generators, not having this option, meet the generation requirements of the system simply by matching RPM and torque models. For this reason it is possible to develop a plot directly relating load and efficiency. Some examples of diesel generator plots can be seen in Figure 4-5. The sections of this paper that mention generator efficiency will use these plots as a reference. The simulations discussed later will also use a structure similar to this; the exact plot can be seen in the simulation section. These figures also demonstrate why many single-speed generators are very inefficient while being operated at partial load. The job of the hybrid system is to “push” the operating point of the generator system to higher loads, resulting in more efficient operation conditions.

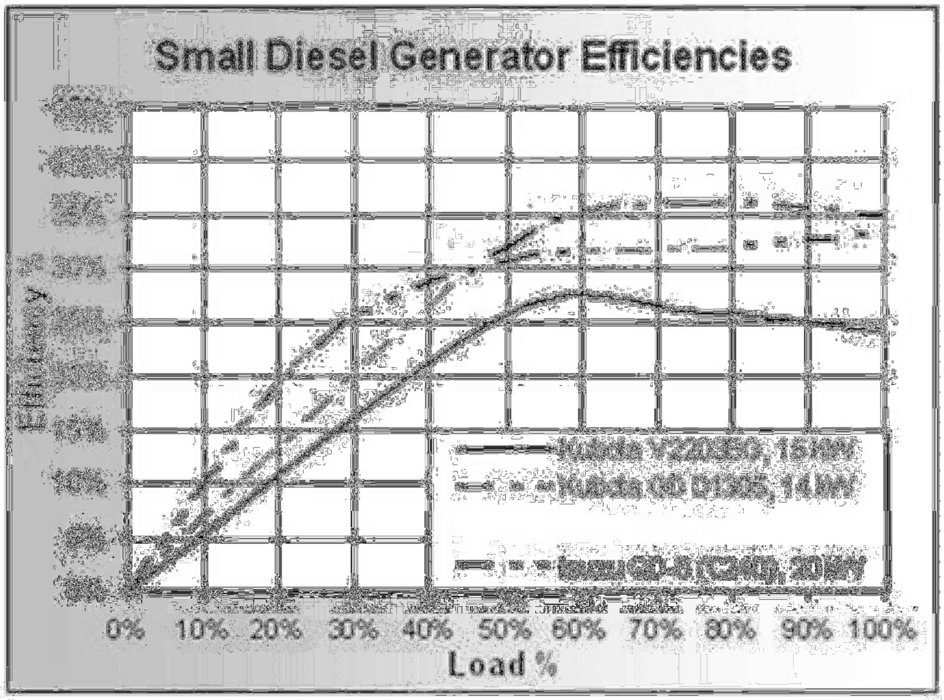


Figure 4-5: Plot comparing load and efficiency for diesel generators. [25]

4.3 Renewable Energy System

There are many benefits to running a hybridized power generation system over a standard generation system, one of which is the ability to receive and store power from many different possible power sources. One such unique source that can be taken advantage of is the ability to receive power from a variety of renewable energy. Renewable energy is defined as any energy that is created by sources that are continually replenished; wind, solar, tidal, geothermal, etc. The two most common renewable sources, for mobile projects similar to this, are solar energy and wind power.

Solar energy is captured with the use of a solar panel, a connected system of photovoltaic cells. Solar panels are rated by the DC power output under testing conditions, usually ranging from 100 to 500 Watts for portable systems. [26] The photovoltaic cells, or solar cells, convert the energy of light directly into electrical energy using the photovoltaic effect. Most modules use wafer-thin silicon-based cells in construction. The individual cell members need to be protected from moisture and physical damage due to the basic material properties of the cells. Most panels are designed to be rigid; however, some fairly flexible panels can be designed.

Solar cells can be arranged, in a mixture of series and parallel configurations, into a solar panel to obtain the voltage and current required for the system. The cells, connected to each other and the rest of the system, often use bypass diodes in case part of the panel is exposed while the other half is under shade. This maximizes the output energy of the still-powered panels.

Solar panels, depending on the design and fabrication, can use energy input from a wide range of light frequencies, but cannot take advantage of the entire solar range, most notably infrared and ultraviolet light. Even with all of the recent advances in solar technology, the newer commercial products have a highest solar panel efficiency of around 20% with production energy density value of up to 16.22 W/ft^2. [26]

In this generation system design the photovoltaic cell technology is used as an energy source to charge the battery pack. Electrical energy from the solar panels is regulated using a boost converter to allow proper voltage charging of the battery pack as well as to operate the solar panel at the most efficient point. A model for the solar panel array based on the current and voltage characteristics of the system is seen in Equation 4-1. [27]

$$V = \frac{KT}{q} ln\left(\frac{I_{sc}-I}{I_0} + 1\right); \qquad (4\text{-}1)$$

Where: V = operating voltage
I = operating current
q = electron charge
K = Boltzman constant
T = absolute temperature
I_{sc} = short-circuit current
I_0 = cell's inverse saturation current.

Using this equation multiple operating points can be obtained by varying the short-circuit characteristics and the temperature. Note that the short-circuit characteristics are proportional to the solar radiation. Figure 4-6, below, shows an example of the possible relationships between power to voltage and current to voltage of a solar panel. The figure has been generated using the HIT 205 module developed by the Sanyo Energy Corporation. While this may not be the exact solar panel used in field, it is a valid representation for what can be expected from any solar cell.

An incremental-conductance method can be used for Maximum Power Point Tracking of the overall solar array. This method observes the operating voltage and current readings to be used by the boost converter. The boost converter can adjust the solar system voltage and/or current to reach a maximum power statistic. The interaction between the solar panel, the boost converter, and the Maximum Power Point Tracking method can be seen in Figure 4-7.

As mentioned earlier, the other most common renewable resource used in mobile applications, like this project, is obtained with the use of wind turbines. A wind turbine is an electromechanical system that converter the kinetic energy from wind into electrical energy. When most people think about wind turbines they think about the large grid-connected arrays used to produce commercial power throughout the world. These wind turbines are too large for this project application. However, there are smaller turbines both on and off the grid.

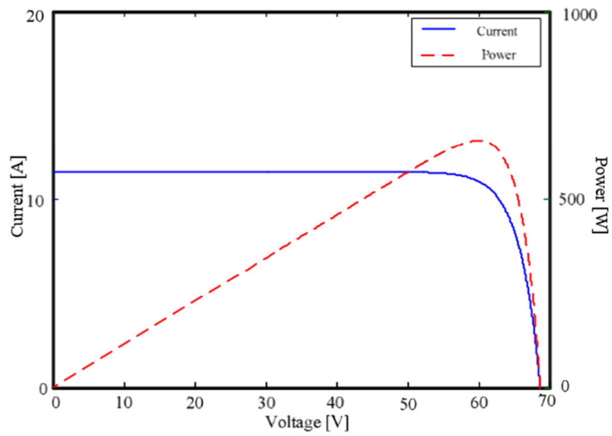


Figure 4-6: Current and voltage characteristics of a solar panel. The figure generated above is based on the HIT 205 module developed by the Sanyo Energy Corporation. [27]

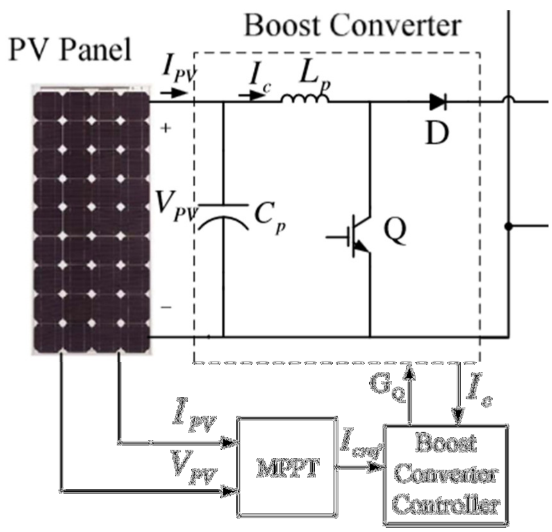


Figure 4-7: Possible layout for a solar panel system. [27]

The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) defines small turbines as any turbine system power output equal to or less than 100 kW, all the way down to 50 W generators used on boats and caravans. The range of wind turbines more suitable for this project will be around the 2-5 kW range. Most small turbine systems often use direct drive generators, aeroelastic blades, and utilize the use of vanes to point into the wind.

The mechanical energy produced is converted to electrical energy with the use of a permanent magnet synchronous generator system. The possible power generated from the turbine system is directly proportional to the cube of air interacting with the blades of the turbine; a formula describing this energy can be seen below, Equation 4-2. [27]

$$P_w = \frac{1}{2} C_p(\beta, \lambda)\rho A v^3; \tag{4-2}$$

Where: ρ = density of the air
A = Air swept by the blades
v = wind speed
C_p = power coefficient of the wind turbine
β = blade pitch angle
λ = tip speed ratio

As a rule of thumb, the maximum usable wind power is approximately 2/3 of the total available wind power. The turbine is systematically controlled by adjusting the electromagnetic torque applied on the system by the permanent magnetic generator system. The system can be implemented similar to how it is shown in Figure 4-8.

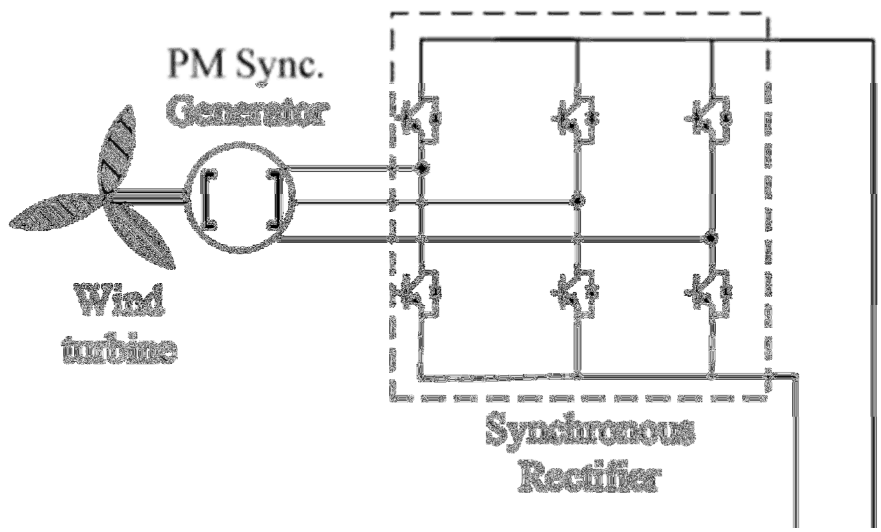


Figure 4-8: Possible layout for a wind turbine system. [27]

Hybrid renewable energy systems have recently grown in popularity, especially in remote or underdeveloped areas requiring generation applications, due to the multiple advancements in several of the renewable energy subsystems, as well as the rise in prices for petroleum products. A hybrid energy system usually consists of two or more renewable energy resources used in conjunction with each other in order to provide sufficient reliable energy. A block diagram demonstrating a possible construction for a solar panel and wind turbine hybrid energy system can be seen in Figure 4-9.

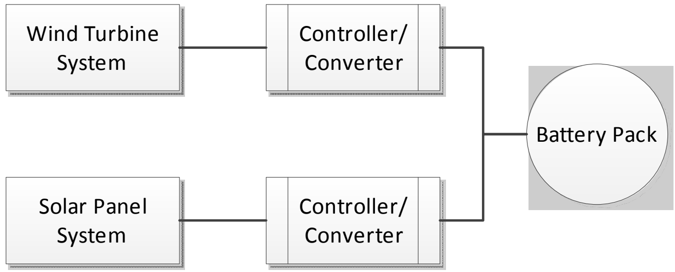


Figure 4-9: Block diagram of a hybrid energy system. It takes into account both Wind and Solar energy.

When designing specifically for the HEATS system a large range of possible wind turbine inputs is a reality, so a more general overall design is required. Solar systems, while usually not as powerful as wind turbine systems, are more mobile and are more common than portable wind turbine systems. One such system that can be designed for is the Navy's new Ground Renewable Expeditionary ENergy System (GREENS). [28] The GREENS is a portable 300 watt hybrid battery generator that uses a solar array as a power input and can be seen set up in Figure 4-10.

Figure 4-10: Navy's GREENS solar array in use. [28]

4.4 Scavenged Power System

A key concept of the hybridized generation system is the ability to accept multiple different power inputs to supply useable power, and charge the battery pack during lower load times. So far generating and storing power through an on-board generation system and a multiple-source renewable energy system has been discussed. In addition to these, the HEATS system is also capable of utilizing "scavenged power". Scavenged power can be thought of as a power source from an already existing grid power system.

By our definition scavenged power can be available at a wide variety of different sources, varying in voltage, power, and even types. For this project, it primarily focuses on three of the most readily available power sources: 120 VAC (standard wall power), 24

VDC (common military grid system), and 12 VDC (common output of smaller power sources including most automobiles).

Standard wall power, or Mains electricity, is the standard general purpose 120 VAC 60 Hz power that can be found just about anywhere inside the United States.[29] The standard voltage and frequency power vary around the world depending where you are, as you can see in Figure 4-11. The US standard is not the most common standard power worldwide, 220 VAC 50 Hz is used by more countries than any other standard.

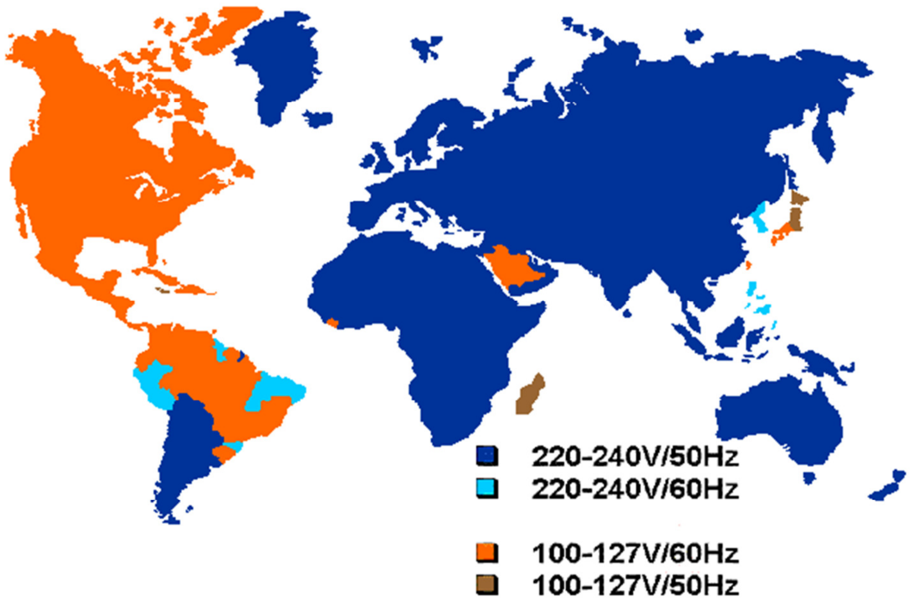


Figure 4-11: Standard wall power around the world. Note the variety of voltages and frequencies. [29]

In an AC, alternating current, power source both the voltage and current supplied are sinusoidal. The kind of load on the system can actually change a lot of the properties of the source. If the load from the AC supply is a completely resistive load, then both the current and voltage reverse the polarity of their signal at the same time. This creates an instance that at every point along the sinusoidal curve the product of the voltage and current, power, is positive. In this instance all the power transferred is considered real power. On the other hand if the load is purely reactive, the opposition of a circuit element to a change of electric current or voltage, both the voltage and current are 90 degrees out of phase. In this instance, half of the power cycle is positive and the other half is negative. On average as much energy would flow towards the load as flow back to the source. This creates a no net energy flow case in this system. A system load's inductance or capacitance causes the electrical reactance. As a whole, on AC systems practical loads have resistance, inductance, and capacitance, resulting in both real and reactive power. In this system both parts of the load, real and reactive, will power the real loads. This issue is not as important on the power input to the system but will be a much larger issue in the power output section of this paper, which is reviewed in greater detail there.

Standard AC wall outlets in the United States are usually rated to either 15 A or 20 A maximum current. A rule of thumb for continuous loading on AC wall plugs is approximately 80% maximum power, or 12 A and 16 A respectively. [29] Converters and other electronic equipment have been sized accordingly. Figure 4-12 is a simplified diagram of a lithium battery pack's energy conversion and storage system. An energy storage system operating alongside an AC power input consists of three primary subsystems: a $LiFePO_4$ battery pack, a battery management system including a central control unit that controls the operation mode and grid interface, and an AC-DC converter. [30] The system uses an AC-DC rectifier to invert the standard AC signal to a useable DC signal, including voltage and current levels, used to charge the battery pack. In the system is a safety contactor that has been placed in order to isolate the battery pack in case of an emergency.

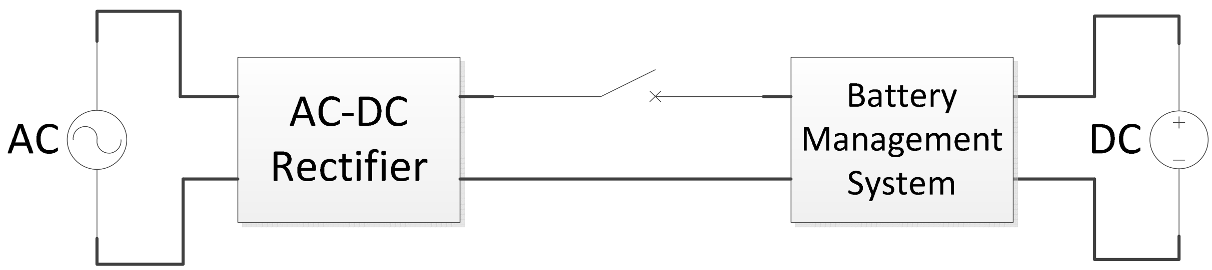


Figure 4-12: Block diagram for an AC charging system.

As mentioned earlier, in addition to 120 VAC power, 12 VDC and 24 VDC power grids are fairly popular and easy to find. A lot of civilian power equipment, both rechargeable and not, run off of 12 VDC systems. This includes anything from standard vehicle power systems to some camping power equipment. Unlike most civilian use, the military uses a standard of 24 VDC for most of the smaller FOB's power grids. 120 VAC is also used at both larger and smaller FOBs but the AC inverter system previously mentioned would be able to handle that subsystem. Both of these power sources will be ran through a DC-to-DC converter to obtain proper voltage to then be handled by the BMS.

As discussed earlier, to charge a battery pack with a larger voltage then the supply sources requires a DC-to-DC power converter. A DC-to-DC power converter with an output voltage greater than the input voltage is a boost converter, which is a kind of switched-mode power supply. The input power for a boost converter can be supplied by a number of appropriate DC supplies, such as batteries, rectifiers, generators, solar panels, etc. A boost converter is also referred to as a step-up converter due to the nature of stepping the supply voltage up. Because power cannot be increased, the current is lowered proportionally as voltage is increased. Actually, with most boost converters having an efficiency of around 80-90 percent the current would decrease at a faster rate than the voltage would increase.

The key concept that the boost converter uses is the inductor has a tendency to resist changes in the current. In Figure 4-13 is a general schematic for a boost converter. There are two different configurations possible in the system, the switch "S" closed, red line in the figure, or the switch open, green line in the figure. In the first stage, switch closed, the current will flow through the inductor, L, in a clockwise manner, resulting in the inductor storing energy. The polarity to the left side of the inductor is positive. In the second stage, switch open, the current will be reduced as the impedance has increased. The current of the second stage is opposed by the previously charged inductor, switching the polarity on the left side of the inductor, now negative. The result of this combination in series causes a higher voltage to charge the capacitor through the diode.

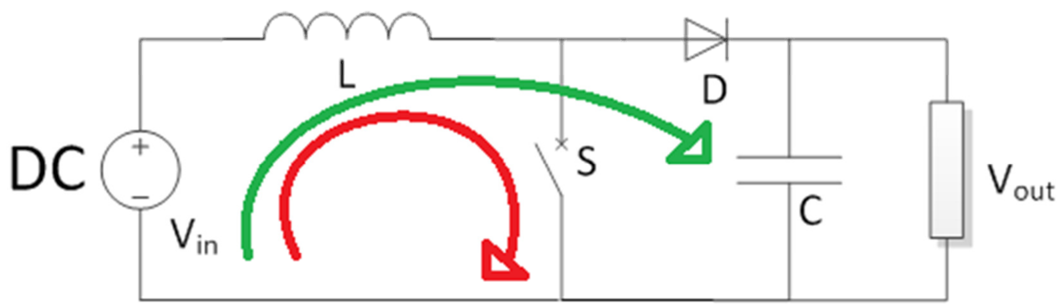


Figure 4-13: General schematic for a boost converter. There are two different configurations possible, the switch open, green line, or the switch closed, red line.

This system is switched fast enough to the point where the inductor will not fully discharge between stages, causing an output voltage always higher than the input voltage when the switch is open. In addition to the higher voltage supply, the capacitor is charged to this combined voltage. When the switch is closed, the side to the right is shorted out of the system. The power provided to the load of the system comes from the capacitor that had just been charged in the stage before. With the switch closed the diode prevents the capacitor from discharging through the switch. These two stages are switched back and forth fast enough to prevent the capacitor from completely discharging.

Chapter 5: Power Output

5.0 Chapter Summary

The objective of this chapter is to demonstrate a design that meets a variety of power supply output requirements and to safely manage the entire output system. The following figure, Figure 5-1, shows how the power output relates to the other parts of the system. In order to complete an efficient and safe design many different output conditions are required to be taken into consideration. Some of the considerations include the variety of possible power output levels and voltages, defining the load prioritization, and determining the load shedding techniques. Control techniques, advantages and disadvantages, will be reviewed and discussed. The power output specifications can vary depending on the vehicle's primary function; however, even with different possible specifications the generalized output and control techniques will remain the same.

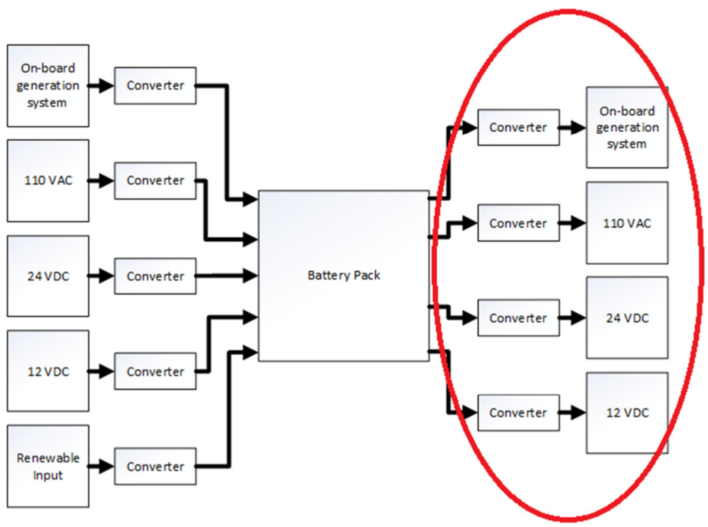


Figure 5-1: Block diagram of system highlighting power output.

5.1 Power and Voltage Output Ranges

Most standard portable generation systems usually only have one kind of output that can be utilized by the variety of loads; AC power in standard generation systems and usually 24 VDC in military environments. To maximize the utility of the hybridized generation system, the system itself has been designed to handle a high variety of possible voltage and power level outputs. In most environments, the most common voltage outputs are, 120 VAC, 24 VDC, 12 VDC, and 3.3 VDC.

As mentioned earlier, 120 VAC 60 Hz is the standard US wall power and while this is not the most common standard wall power worldwide it is the design criteria chosen for the system. The inverter specifications can be modified, or added, to meet any type of AC power requirements necessary, with the generalized design staying mostly the same. To transform the DC battery pack power into useable 120 VAC power, the energy must be run through a power inverter. The power inverter can convert DC power to an AC signal ranging in any required voltage and frequency using an appropriate arrangement of switching, transformers, and control circuits. For this application a solid-state inverter is most appropriate for the system design. The solid-state inverter has no moving parts and is very common among a wide variety of applications. These applications can be used in anything including small switch power supplies used in computers, large electricity utility high-voltage direct current applications used to transport large amounts of power, and are common when used to provide AC power from large DC sources like solar panel arrays and battery packs.

There are a significant number of factors that must go into selecting the best inverter for the given applications, especially when the higher power ranges are required, like the HEATS application. Similar to a battery pack, the inverter needs to match two power level specifications, the surge and typical power ratings.[31] The surge rating, or the peak, is the maximum power that inverter can supply for a short time. This time can range anywhere from only a few seconds to possibly 15 minutes or longer. Depending on the possible loads, some applications require a higher startup surge than others, especially pumps, compressors, and refrigeration units. These higher power requirement sources are common among a wide variety of applications. For this reason the system has been designed to accommodate a surge load of up to approximately 18 kW, the rating of the inverters/converters are reviewed later.

The typical power rating is what the inverter is capable of providing in a steady state basis, also known as the continuous rating. This rating is normally much lower than the surge rating. Many loads, like the refrigeration system mentioned earlier, start at a much higher load but after the first few seconds the load drops to a lower running power requirement. In addition to the other ratings, the average power load the system is sized for is normally much less than either the surge or typical ratings. However, this factor is not normally very important when sizing an inverter, but is much more useful when estimating battery pack capacity requirements.

There are three major types of inverters that are commonly used in everyday applications. The three output signals can be seen in Figure 5-2. The most simple, and cheapest, converter on the market is a square wave inverter. This inverter will only run simple tools with universal motors and not much else. These inverters are rarely seen anymore and will not work for the HEATS application. The second type of inverter is a modified sine wave that actually generates a square wave but with a few extra “steps” per cycle than the standard square wave. Most equipment will work on these systems, but will normally use about 20% more power to do so. [31] The sine wave being more like a square wave also means that some appliances will not operate correctly, some applications can use the input signal as a way to mark timing scenarios but operating on a nosier signal can result in quality complications. The last and highest quality inverter is a sine wave inverter that produces a signal seen straight out of the wall or off some AC generators. Using this standard sine wave inverter ensures that all standard AC equipment works properly. These inverters are the highest quality but are also usually much more expensive, normally about 2 to 3 times as much.

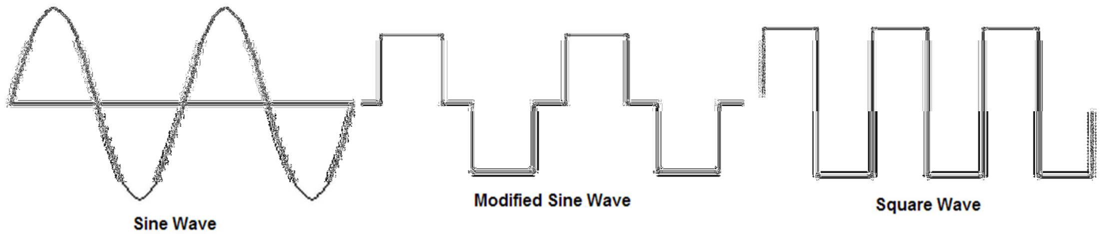


Figure 5-2: Variety of possible AC inverter output signals. Output signals for the three different types of AC inverters: Sine Wave, Modified Sine Wave and Square Wave. [31]

As mentioned in the AC power input of the section, practical loads have resistance, inductance, and capacitance built into the system so both real and reactive power will flow to the real loads. Also mentioned earlier, in purely resistive loads only real power is transferred and in purely reactive loads the voltage and current are 90 degrees out of phase. In purely reactive loads, no net energy flows into the load. Apparent power is measured as the magnitude of the vector sum of real and reactive powers. Apparent power is the product of the root-mean-square of the voltage and current. When designing circuits, apparent power is important to the design because while the current related to the reactive power does not make it to the load, it does heat the wire and waste a significant amount of energy. When sizing equipment, such as generators, the total power must be taken into consideration and not just the real power. The AC inverter must be capable of dealing with the issues of the power factor. The power factor is defined as the ratio of the real power to the apparent power, and is a dimensionless number between -1 and 1. Capacitors are normally used to generate reactive power to use in conjunction with inductors that consume it. If the two components, the inductor and the capacitor, are placed in parallel they tend to cancel each other out rather than add. This is the generalized mechanism for controlling the power factor in electrical transmission. Reactive power, and voltage levels, must be carefully controlled to allow a power system to be operated within acceptable limits.

Besides the DC to AC inverter previously mentioned, the remaining power supply sources are all step down DC to DC converts. The simplest way to reduce voltage from a DC power supply is to simply use a linear regulator; however, linear regulators waste a significant amount of energy that is then dissipated by heat. However, buck converters can be used in place and can have a very high efficiency, as high as 95% depending on the circuit complexity. The design for this converter is very similar to the boost converters discussed in the power supply part of the report, most of which being a switched-mode power supply that use a number of switches, diodes and transistors, and capacitors and inductors. A generalized basic circuit diagram for a buck converter can be seen in Figure 5-3.

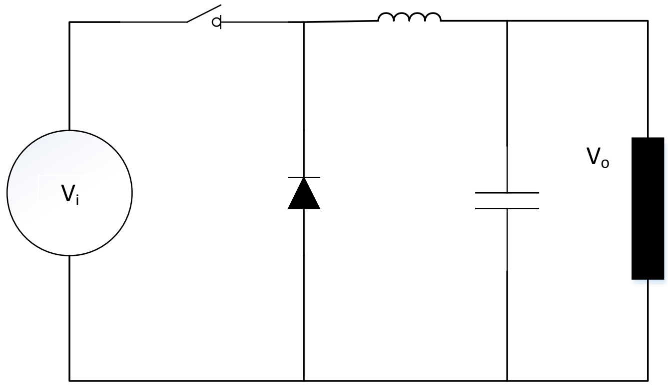


Figure 5-3: Basic circuit diagram for a buck converter. The system has two different states: the switch open and closed.

Designing the overall output system requires understanding the kinds of loads that each type of output can expect to see. These possible load ratings can vary depending on several different scenarios, specifically the final user. For example, use in a military setting would require a much higher 24 VDC power supply than most civilian equipment seeing as how unpopular 24 VDC is on nonmilitary settings. Overall, both 24 VDC and 120 VAC are fairly popular for use in larger, higher-powered equipment whereas 12 VDC and 3.3 VDC are more popular under low-power continuous conditions. Having developed multiple load estimations, Table 5-1 has been created to show the estimated converter and inverter sizing information. The table shows both the continuous and maximum proposed rating for each of the components required.

Table 5-1: Output converter ratings.

110vAC	24vDC	12vDC	3.3vDC
6 kW	10 kW	2 kW	0.3 kW

The various inverters and converters to meet all of the requirements for the HEATS system requires a very specific design that does not meet popular enough demand to warrant the wholesale of the exact specified components. For this reason the systems would have to be custom manufactured by a company similar to Vicor Power or Nova Electric Hi-Rel AC Power Systems.

When looking at all four components of the output systems the total combined output power of all of the converters and inverters exceed the maximum continuous output power of the system. If summed up the total possible power output of the system is approximately 18.3 kW for military scenarios. While the battery pack can be a "buffer" for power exceeding that of the generation capabilities, 10 kW for the on-board generator set, eventually the battery pack will drain to a minimum operating point and if the load remains excessive of the generation capabilities some of the less important loads must be stopped. For this reason load prioritization and load shedding schemes are required to maintain a safe and stable system. In any power generation system with a variety of loads, the loads themselves will have a varying importance level among them. Load prioritization is how the load shedding scheme understands what loads can be severed and which loads are most critical for the operation purpose.

5.2 Load Prioritization & Load Shedding

The ability to safely control and monitor the overall output of the system is critical to the system design. Standard single power generation systems can monitor the output of the system and can warn the user if the load exceeds, or becomes close to exceeding, the generation potential. The hybridized system has the advantage of being able to use battery power to make up additional power requirements for the load. This additional power is not continuous; the battery pack can be used until the pack reaches a predetermined lower level state of charge. If the load continues to be excessive, once the lower level state of charge is reached, the hybridized system has the capability to perform load shedding to get rid of the lower priority loads on the system. The priority of the loads is to be set by using a user-generated interface, also referred to as a GUI, by whoever is using the system.

This GUI is the major interaction point between the user and the equipment. In addition to being able to set the load prioritization order, the running system information can be seen from this menu. This includes, but is not limited to, battery state of charge tracking, system health information, generator operating information, power output tracking, and any other critical information required. Similar GUIs have been designed using National Instruments's LabVIEW software. The central hub of the system uses a standalone smaller computer; a fitPC has been previously used on other similar projects. Additionally, on the vehicle an information transfer hub is used to communicate between the central hub and the other monitoring system via an Ethernet connection. A previously developed GUI for the original HEATS vehicle platform can be seen in Figure 5-4 below. A GUI similar to this would be developed for the hybrid generation system. Each system can be monitored in its individual tab, the prioritization of the loads can be set in the 'Load Prioritization' tab, and the important information for the charging scheme can also be set in its own tab. With use of the central computer, a wireless router, and LabVIEW it is possible to monitor, and even control, the system, wirelessly using LabVIEW's webserver protocol. Using this protocol the system can be monitored or controlled from any computer, or even Smartphone, on the same network.

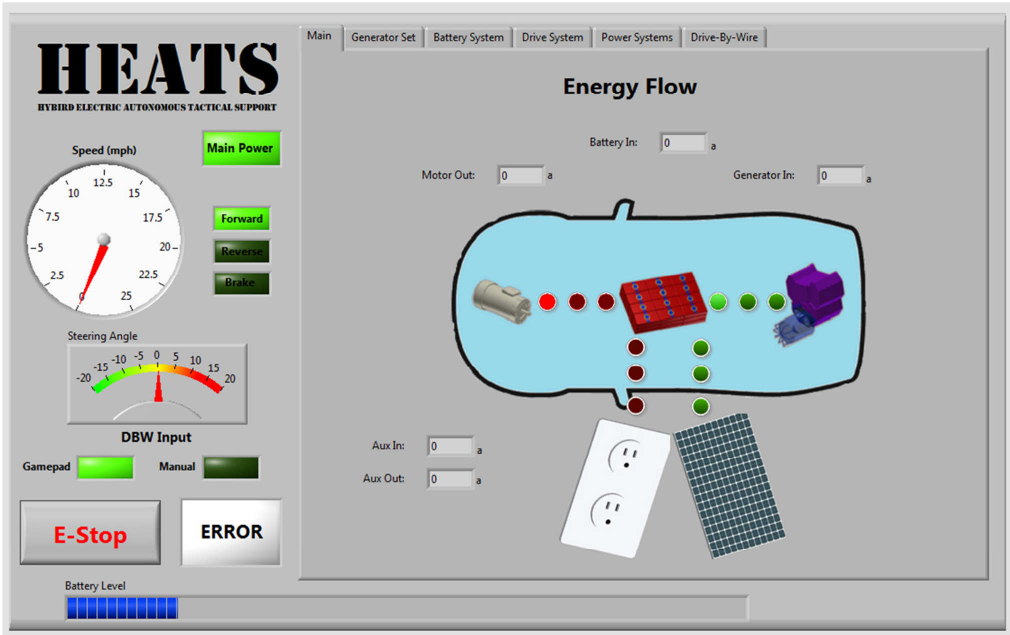


Figure 5-4: GUI previously developed for original HEATS project. The GUI developed could be similar to this one.

Being able to set and monitor the system's critical information is necessary in order to fully take advantage of the capability of load shedding. Load shedding is a term used to identify purposely switching off electrical supply loads of an electrical network. Load shedding usually refers to a method that helps to protect the overall stability of the national power grid. However, the general concepts behind load shedding remain the same for both large and small systems. Load shedding can be utilized when an imbalance between power load demand and the power supply is detected. When the supply power reaches this imbalance there can be a requirement to reduce the output to a more acceptable level or risk the entire system shutting down, or possibly even system damage. There are usually two different methods in load shedding: automatic load shedding and manual, or selective, load shedding. Automatic load shedding is a result of detected errors or scenarios in which the computer system detects loads that are required to be relieved. The system then looks at the load prioritization and cuts the loads at the bottom of the list, until proper load levels are again maintained. This is how the system should operate in most excessive power situations. Manual load shedding is more of an option in case there is a malfunction with the equipment using the HEATS power system. The manual load shedding would be most useful for more unique scenarios. The effectiveness of a load shedding system depends on the proper identification of the generation system and load characteristics. [32]

In order to monitor and control the system as specific as possible each output line has been outfitted for both monitoring and shedding capabilities. A system diagram showing the load shedding technique for the system can be seen below in Figure 5-5. Each of the output lines, there are four lines per each load type, has been designed with a current monitoring hall effect sensor ring, the red circle in the figure below, and a solid state high power relay, the switch icon in the figure. Using the load prioritization discussed earlier, the system is capable of monitoring the individual outputs to each load and disconnect the lower priority loads if the output requirements exceeds capability.

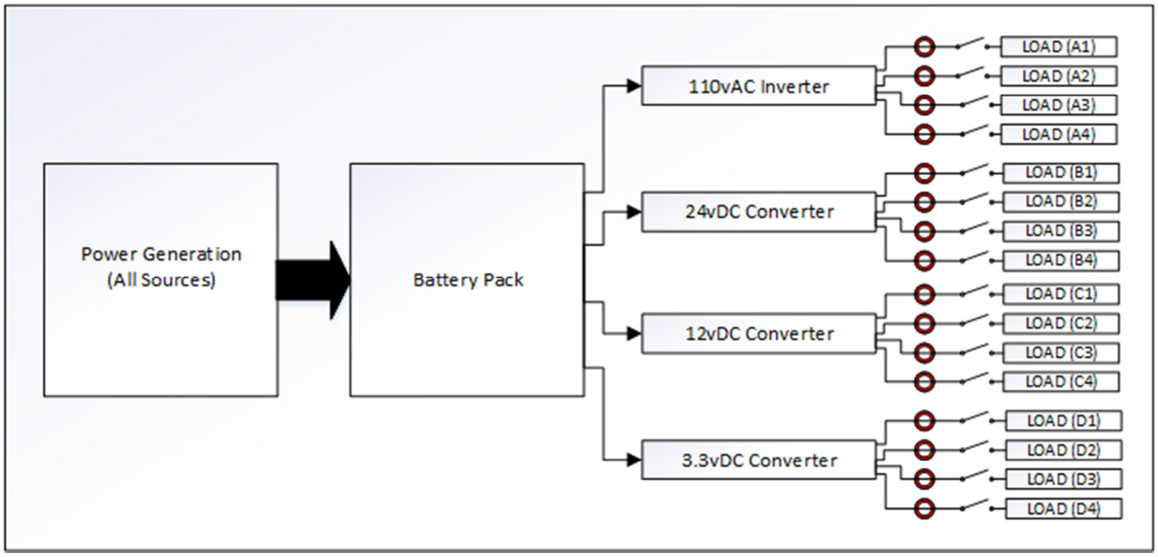


Figure 5-5: Diagram for load shedding technique. Note that every output line has a current monitoring Hall Effect sensor, red circle, and a solid state relay, switch icon, in order to monitor and shed the loads.

With a system developed capable of monitoring both the input and output systems as well as being able to shed the excessive load when necessary, a general control scheme is required for automatic load shedding. Figure 5-6 shows a flowchart with one such basic control scheme. The basic idea of the load shedding scheme is to first identify what the total power out of the system is. This has been broken up into three general categories: overall excessive power level (over 18 kW), acceptable power level with a suitable amount of charge in the battery pack (10 kW to 18 kW), and an overall acceptable power level even with an empty battery pack (under 10 kW). If the power requirement is greater than the overall excessive power level the system periodically disconnects the lowest priority load in the system until the total load is under the excessive power level. If the output load is between 18 kW and 10 kW the first step is to check the battery state of charge to determine if the system can supply the excessive power with the battery pack itself. If the battery pack does have a high enough state of charge, programmable but left at 30% for this example, the system does not disconnect any loads and continues to operate as intended. If the battery pack state of charge is under the allotted amount the system would then disconnect the lowest priority load until the overall load is less than 10 kW. If the overall output load starts under 10 kW then the first step is to check the battery state of charge. If the state of charge of the battery is under a higher level state of charge, 80% was used for this scheme, the system returns to the beginning state without any other system interaction. If the battery state of charge is over the higher level the system reconnects any of the previously disconnected loads and the system returns to the beginning of the control scheme. This control scheme is intended for continuous operation and also takes into consideration any manual load shedding the user requires.

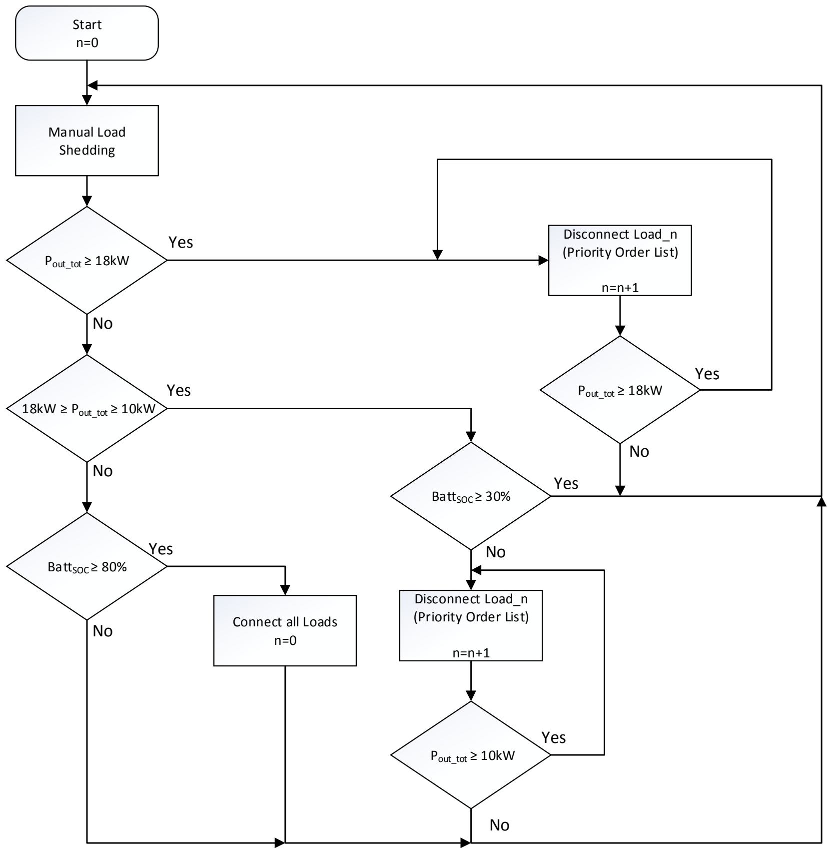


Figure 5-6: Flowchart showing load shedding control scheme.

The entire reason for load prioritization and load shedding in the system is to increase safety and stability in the system by being able to control and monitor the overall output. Unlike standard power generation systems, the hybridized system has the ability of being able to take advantage of the battery pack when it comes to meeting the requirements of high load scenarios. While not able to continuously meet the excess load, the battery pack can be used until a preset lower state of charge is reached. The ability to control each of the output loads individually grants a lot of technical advantage to the hybridized system.

Chapter 6: System Simulation

6.0 Chapter Summary

To measure the effectiveness of the hybridized generation system, the hybrid system's overall design needs to be compared with an unmodified standard generation system. For this comparison several simulations have been constructed using MATLAB software for both the standard and the hybridized systems. These simulations are essentially energy conservation equations throughout an operation period. Before simulation could be developed, basic system statistics were established for both of the power generation techniques. As mentioned earlier in the report, both of the systems, the standard and hybridized, operate with a 10 kW generator. For this generator a theoretical load and efficiency plot has been developed, as seen below in Figure 6-1. The same plot will be used for both of the generator sets so we can compare just the hybridized aspect of the system, and not the generator itself. It is important to note that the maximum efficiency of the generator system can be found between 70 and 80% load. This theoretical efficiency plot has been developed using several different generator plots and can be thought of as an appropriate average.

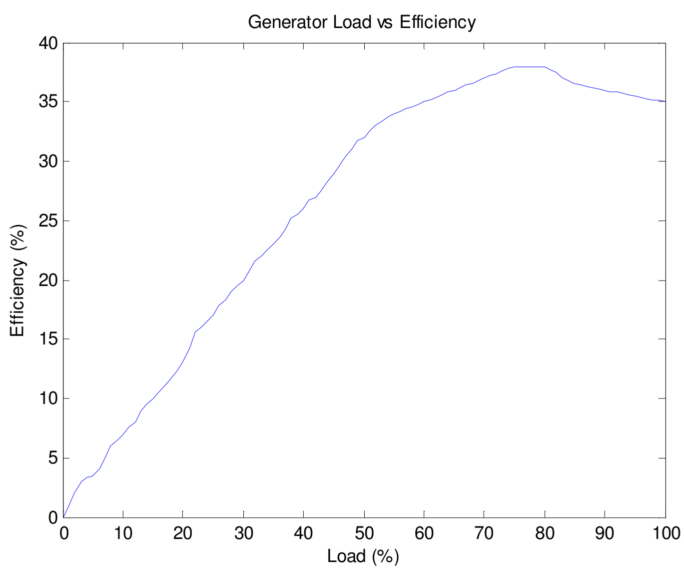


Figure 6-1: Theoretical load vs. efficiency plot for the generator. Note that the generator has maximum efficiency between 70 and 80% load.

For the simulations performed, five different loading schemes have been developed: low power requirements, high power requirements, medium (drop-off) power requirements, highly varying power requirements, and a profile more correctly matching forward base scenarios. The loading schemes used can be seen in Figure 6-2. Each power scheme was developed to estimate a different loading scenario; most of the scenarios have a requirement spike during the day, with a lower requirement during the night. The low power profile represents how a lot of generators are used regularly. When a generator set is picked, it is chosen based on the maximum requirements the generator could see. If it is not sized in this manner the application the generator is chosen for can suffer greatly. Most of the operating times of a generator lay within this scenario. This profile is one of the reasons for the hybridized design. The high profile represents the kind of scenario the original generator was chosen for. This represents the highest average power requirements the generator will see. As stated earlier, generators operate most efficiently at higher power loads, for this reason this scenario is actually the least beneficial. The last three scenarios, medium profile (starts off at a medium load and drops off rapidly), the varying loads, and a realistic model are more unique scenarios. The medium profile represents dealing with a fairly high load for part of the day then having the load drop off dramatically, whereas the varying profile bounces back and forth between high and low loads, representing any kind of non-continuous equipment loads. Lastly, the actual profile represents a realistic model that has been obtained from forward operating bases. The reason this is still considered a unique scenario is due to the low power levels compared to the overall system.

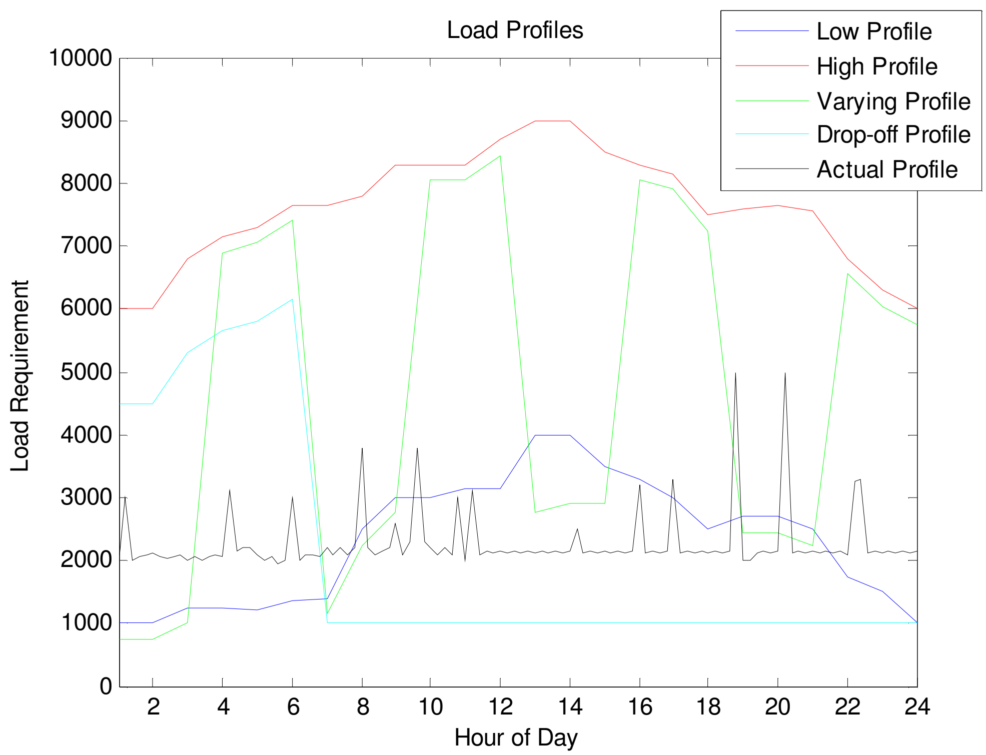


Figure 6-2: The loads schemes used for the simulation testing. All of the loading schemes are based on 24-hour simulations using one hour load increments. The "actual load" is realistic load pulled from an outpost.

6.1 Standard Generation System

The standard generation system is a simple generator that produces energy to meet the moment by moment power requirements. A schematic for a standard generation system can be seen below in Figure 6-3. Meeting power requirements in this fashion allows the generator's efficiency to greatly fluctuate depending on loading scheme.

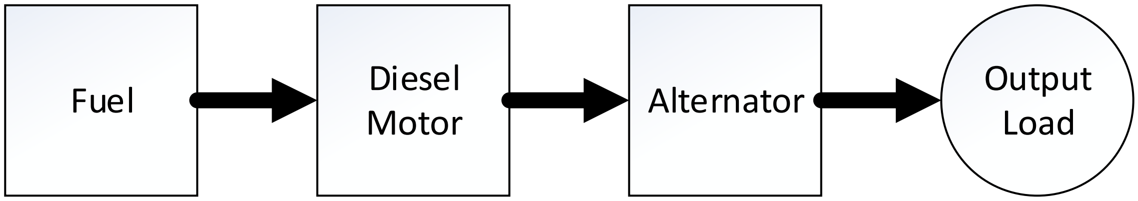


Figure 6-3: Generalized schematic for standard generation system. This system meets energy requirements as necessary.

Depending on the operating load of the standard generation system, the generator's efficiency can highly differ greatly as u can be seen in Figure 6-4. This figure compares the instantaneous running efficiencies throughout the operating duration, 24 hours, for all of the different profile schemes. This figure easily demonstrates how the increased load can result in a higher running efficiency. The hybridized system is designed to take advantage of the lower efficiency time periods.

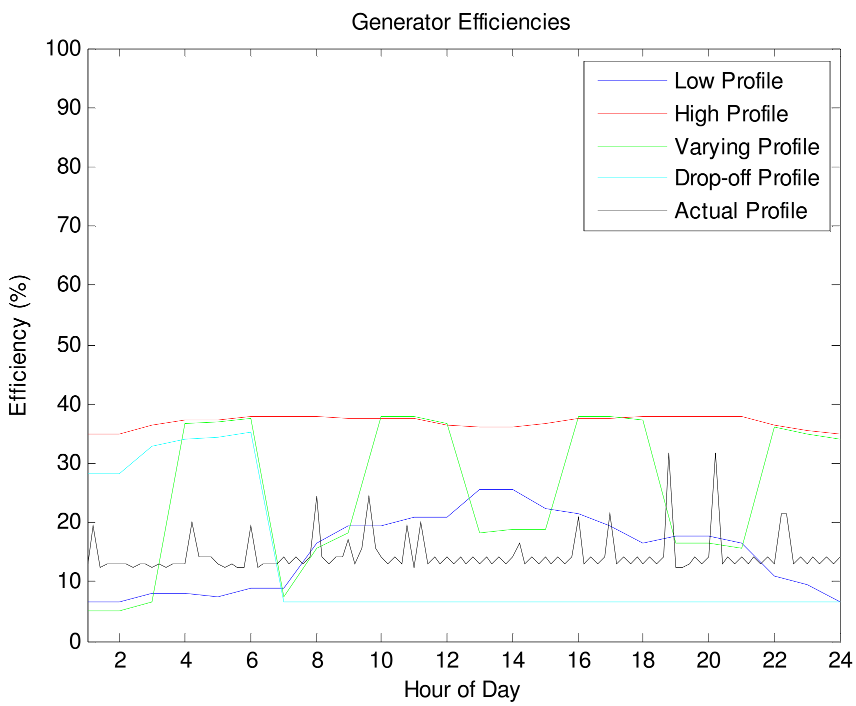


Figure 6-4: Efficiency fluctuation for standard generation system. Even operating the generator at the most possible efficient point results in fuel energy to output ratio of about 38%.

Using Figure 6-4, the 24 hour average generator efficiency for each of the loading profiles can be determined; this has been displayed in Table 6-1. As determined earlier, 38% efficiency is the highest the system is capable of producing, with the high demand profile operating fairly close to these conditions. The other profiles on the other hand operate at a much lower efficiency and lose a lot of possible generation energy; an example of this can be seen in Figure 6-5 below. This figure shows the comparison between the amount of fuel energy that is used as input into the generator and the energy output to the load. This information was determined using the Load vs. Efficiency plot discussed earlier and energy conservation equations. The equations used for this analysis are equations 6-1, 6-2, 6-3, and 6-4 as follows. Using these equations for all of the different profiles, critical information can be determined in use for comparing the standard generation system to the hybridized generation system.

Equation 6-1 shows how the efficiency of the generator system was determined for each time step in the simulation. The system looks up the generator efficiency at the given load profile.

$$E_X(i) = E_{Gen}(Load_{x\%}(i)) \tag{6-1}$$

Where: E_x = Gen Efficiency of profile X at time step i (Unitless)
E_{Gen} = Gen Efficiency profile of the generator (Unitless)
$Load_{x\%}$ = Percent load of profile X at time step i (W/kg)

Equation 6-2 determines the Fuel power requirement for each time step of the generation system. This includes both the load and the energy wasted in the system. This involves determining the efficiency of the generator at each time step and then working that into the load onto the system.

$$F_x(i) = \left(\frac{100}{E_x(i)}\right) * LP_x(i) \tag{6-2}$$

Where: F_x = Fuel Power Required at time step i (Unitless)
E_x = Gen Efficiency of profile X at time step i (Unitless)
LP_x = Load profile at time step i (W)

Equation 6-3 determines the Fuel power wasted due to the inefficiencies of the standard generation systems. This is just the difference in the energy required and the actual load that has to be met.

$$PW_x(i) = F_x(i) - LP_x(i) \tag{6-3}$$

Where: PW_x = Power Wasted at time step i (W)
F_x = Fuel Power Required at time step i (Unitless)

LP_x	= Load profile at time step i	(W)

Equation 6-4 represents the percentage of energy "into" the system that is lost due to the inefficiencies. This is done by simply comparing the fuel power requirement and the energy wasted.

$$PW\%_x(i) = PW_x(i)/F_x(i) \quad (6\text{-}4)$$

Where:	PW_x	= Power Wasted at time step i	(W)
	F_x	= Fuel Power Required at time step i	(Unitless)
	LP_x	= Load profile at time step i	(W)

Table 6-1: The 24 hour generator efficiency average. This efficiency is calculated using fuel energy in compared to generated energy output.

Load Profile	Low	High	Varying	Drop-Off	Actual
Standard 24 hour Average Generator Efficiency (%)	15.06	34.96	26.86	13.28	14.52

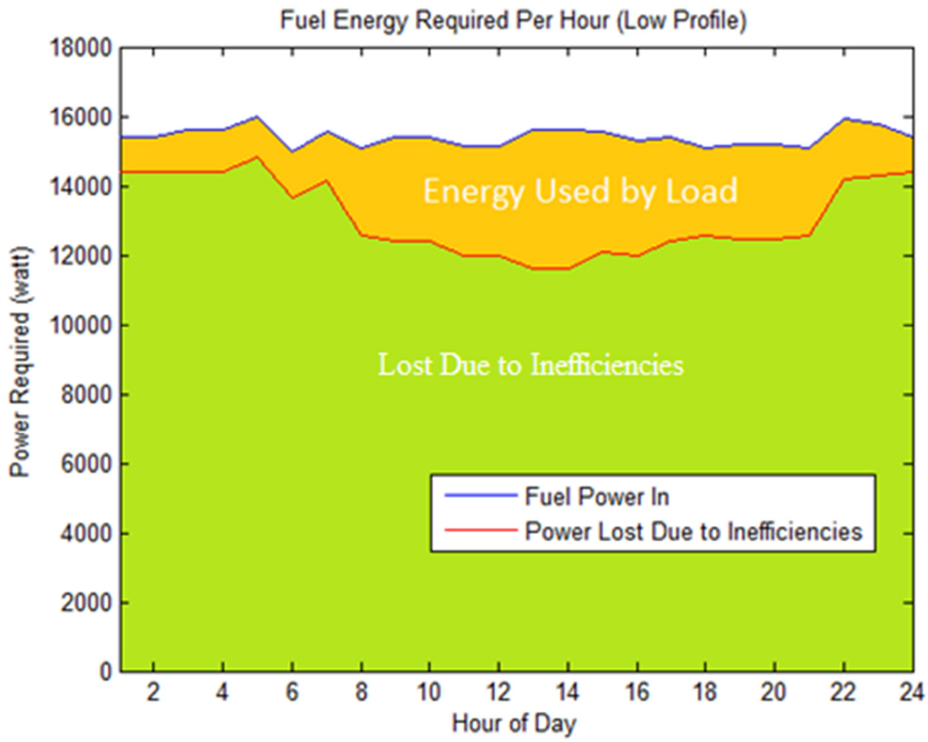


Figure 6-5: Standard system fuel energy into system vs. energy created.

6.1 Hybridized Generation System

Having established a standard generator system's operation profile, the hybridized system now has a baseline to be compared against. Unlike the standard generation style, meeting power requirement demands as necessary, the hybridized system can place additional load on the generation system at lower load times by placing energy into the battery pack. Also the hybridized system can take advantage of additional power sources in the area. Due to the increased complexity of the system, additional control strategies are required on top of the original generator system controls. Figure 6-6, below, shows a generalized schematic for the hybridized generation system including the various possible power input methods. It is important to note that this simulation would apply for any battery pack chemistry as long as two pieces of criteria for the battery pack remain true. First, the charge/discharge efficiency is above 95%. And second, the battery pack C rating is equal to or above the maximum output of the simulation, which for our profiles corresponds to a 10 kW load. A "C rating" is often used to describe current loads onto the battery pack. 1C is also known as a one-hour discharge rate.

In the simulation, most of the power generation input characteristics can be programmatically changed in the beginning of the simulation. This includes the size of the power sources, the starting state of charge of the battery pack, the battery pack key state of charge points, the battery pack size, and the converter efficiencies. In the simulation, power input has been separated into two different power sources: on-board generator and auxiliary input. The auxiliary input is the sum of the 110 VAC, 24 VDC, 12 VDC, and renewable resources power sources. This has been done due to the control strategy for charging. To prevent any internal system damage the hybridized generation system will not generate power from both the on-board generator and the auxiliary system simultaneously. This is due to the power sources having such a high difference in possible power input.

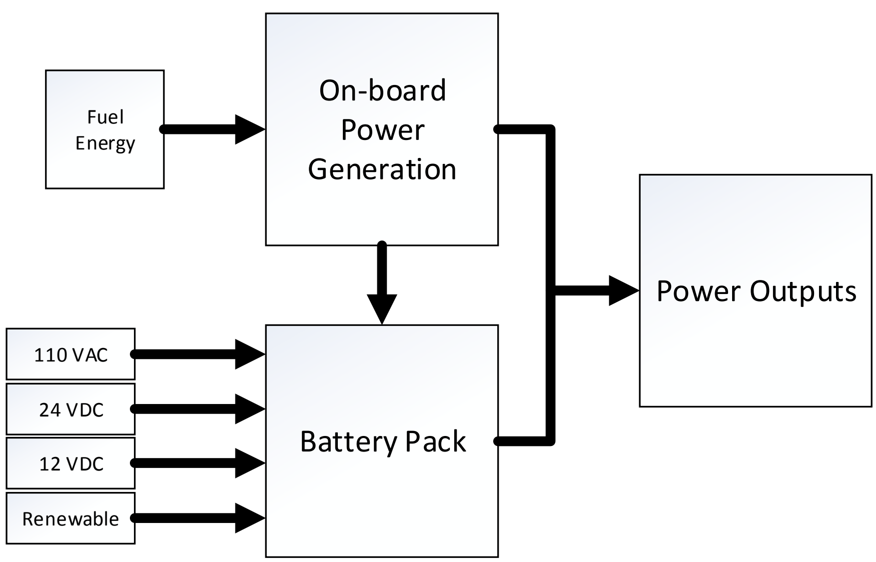


Figure 6-6: Block diagram for a hybridized generation system. This system uses a battery pack to increase generation efficiency.

Having a simulation that relies on so many different variables can be difficult to analyze due to the numerous possible scenarios that can be developed. For the simulations completed on the hybridized platform, several different constraints have been kept constant throughout the testing: state of charge key points, average auxiliary inputs, and the converter efficiency for the entire system; the values for these can be seen below in Table 6-2. In addition the energy equations used in this simulation are the same as the standard simulation, with the addition of the SOC tracking and an equation to determine what the additional load the battery pack needs to put onto the system to achieve the best efficiency.

Table 6-2: Hybridized generator system specifications that were consistent.

SOC Lower Limit (%)	SOC Upper Limit 1 (%)	SOC Upper Limit 2 (%)	Auxiliary Input (watt)	Converter Efficiency (%)
20	80	95	0	87

These aspects can be changed, but have been left constant through the testing because the system will have the same general response to the loads. The SOC lower limit is the lowest point that the battery pack can reach before the generator is activated to charge the system. The SOC upper limit 1 is the point at which the generator turns off; charging the last bit of the battery pack must be completed at a slower rate to prevent damage to the pack. The SOC upper limit 2 is the point at which the battery pack will reject any additional energy into the system. To charge from upper limit 1 to upper limit 2 the auxiliary power systems will be used in a slower charging method. This has been limited to 95% to prevent any damage to the battery in the event of a state of charge calculation mishap. Lastly, the converter efficiency for the system has been set to 87%; this is a value that seems fairly conservative on high end converters. [33] Both of the simulation models, the standard and the hybridized, operate on some of the same general principles.

The hybridized power generation simulation used will include the same generator efficiency plot and characterization load schemes as before, shown in Figures 6-1 and 6-2 respectively. The analysis completed on the system can still have several different changing variables, most important or which is the starting SOC of the battery pack. If the battery pack is full at the start then a fair amount of the load can be dealt with using only the pack itself. Whereas if the battery pack starts almost empty the generator will run until the battery pack reaches the SOC upper limit 1. A generalized control strategy can be seen below in Figure 6-7; these are the basic system guidelines the MATLAB simulation followed. The control strategy of the system mainly depends on tracking the state of charge through the simulation load profiles as well as the load profile itself.

With the use of the hybrid aspect on the system, the efficiencies of the generation profiles can be driven to a higher point. Shown in Figure 6-8, the efficiencies of each of the cycle profiles seem to stay around the same percentage. In the figure it is good to note that when the efficiencies are shown at zero percent they represent a time when the generator is powered off. This figure is the result of a low starting state of charge, 20%, a higher starting state of charge would have the same efficiencies but the generator would be off more often. This figure can be used to determine the 24 hour average generator efficiency, similar to what was done for the previous simulation; this data can be seen below in Table 6-3.

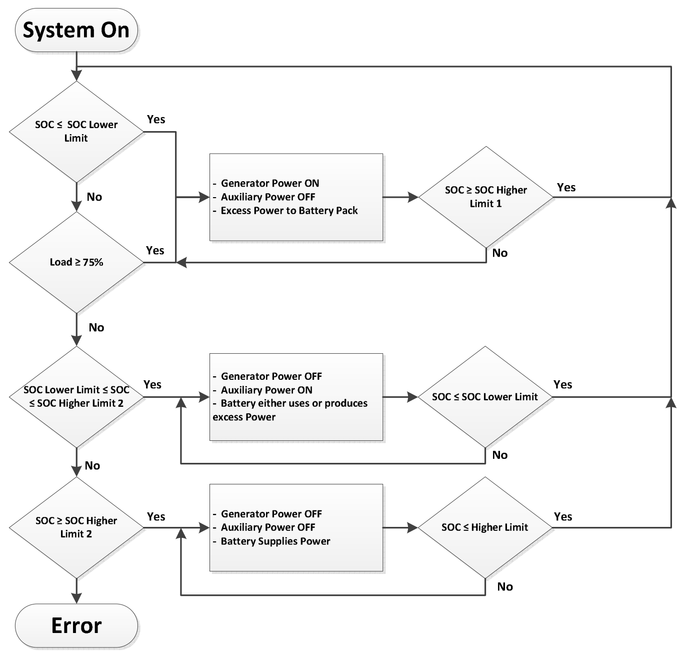


Figure 6-7: Flowchart for control strategy of the hybridized generation system.

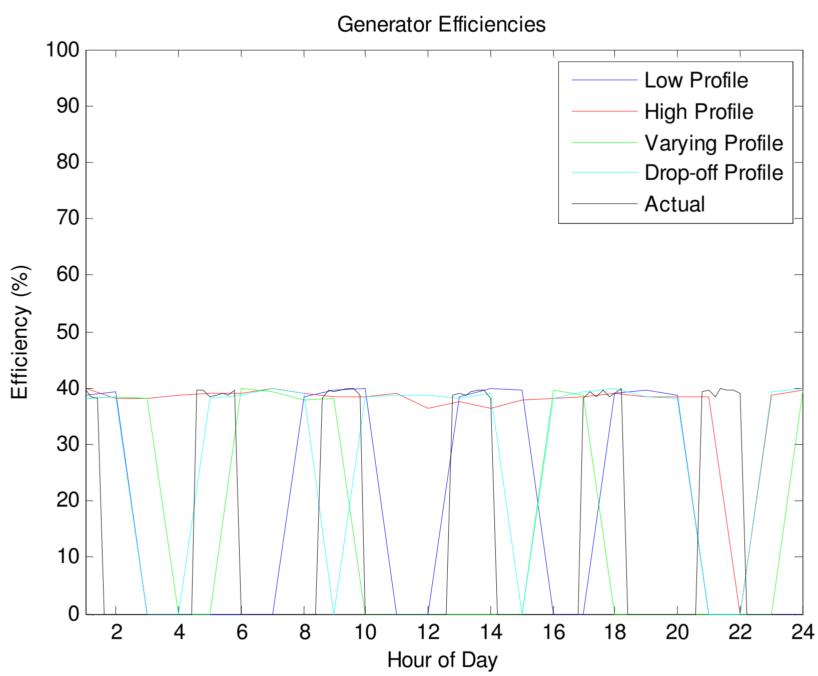


Figure 6-8: Efficiency fluctuation for hybridized generation system. It is important to note when the generator efficiencies drop to zero indicates when the generator is off.

Table 6-3: Hybrid generator efficiency averages.

Load Profile	Low	High	Varying	Drop-Off	Actual
Hybridized 24 hour Average Generator Efficiency (%)	36.10	36.05	35.85	36.10	36.10

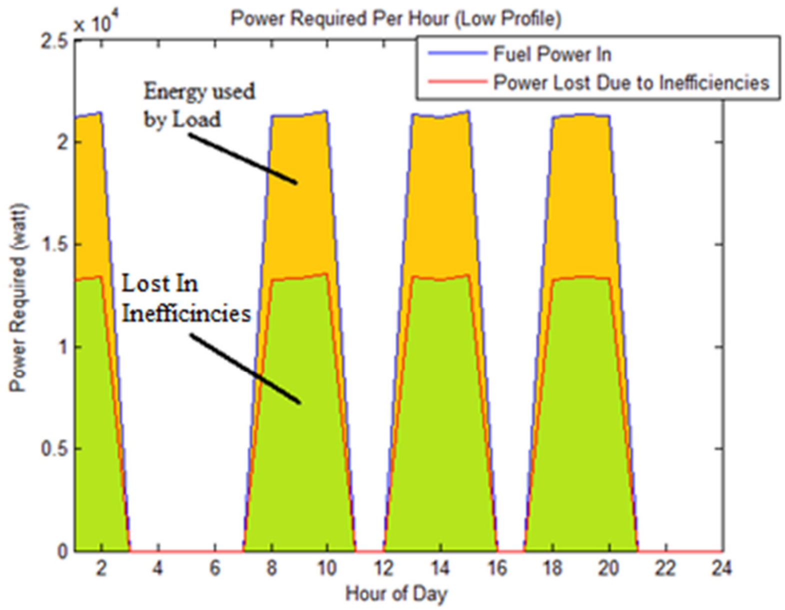


Figure 6-9: Hybrid system fuel energy into system vs. energy created.

In addition to the system comparison, that has been reviewed, the simulation also tracks the hybrid system's reaction to the loading scenarios. Below, in Figure 6-10, is an example of tracking the SOC of the battery pack during a full 24 hour cycle. In this example, the loading profile used is low and the starting state of charge is 20%, labeled A in the figure. The point B in the figure labels the higher state of charge 1, set to 80% for testing. The slope C shows the time at which the system was using on-board generation to meet load requirements and charge the battery pack. That section labeled by D designates the section of time with the energy input into the system being provided from the auxiliary systems with excess power output provided by the battery. It is important to note that the SOC increase while the generator system is off is due to the fact that the auxiliary inputs are actually higher than the load onto the system. Other plots have also been generated, including a plot designating whether or not the generator is on or off depending on the requirement. As expected, the generator set operates much more frequently during the higher loading scenarios. All of these plots have been generated and can be found in Appendix A.

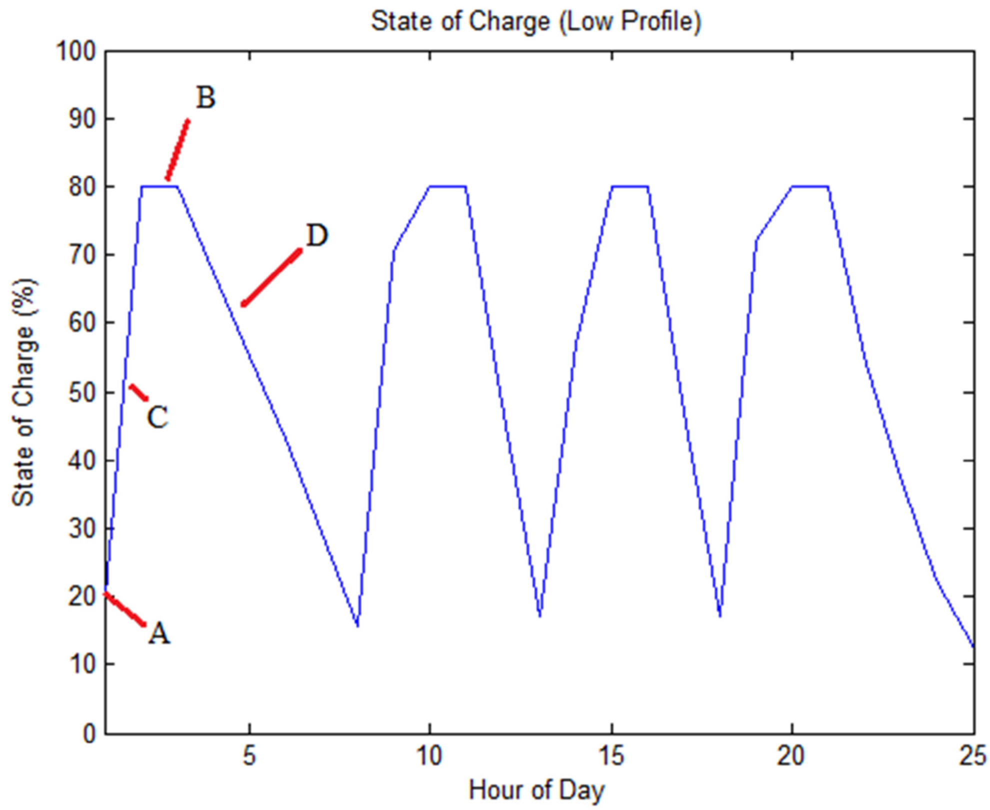


Figure 6-10: SOC tracking for the low profile testing. In this example a starting SOC of 20% is used. A is the starting state of charge. B is the higher state of Charge 1. C is the portion of time that energy generation is created by the on-board generator. D is the portion of time with energy input from the auxiliary systems with excess output provided by the battery.

6.2 System Comparison

As seen from the average efficiencies, the hybridized system is more beneficial in lower load scenarios, as mentioned earlier. In addition, a figure comparing the total amount of fuel energy into the system compared to the energy output to the load, as well as stored in the battery pack, can be seen in Figure 6-9. At first glance it appears that the energy lost in the system is still very high, however when compared to the original energy generation system, this ratio is a vast improvement. The overall efficiency comparison of both can be seen in Table 6-4. This shows an efficiency rating as high as 36% for the hybrid system on the low load scenario, as compared to the 16% of the standard system. Similar to the previous analysis, this figure has been developed using the low profile scenario with the rest of the program outputs found in Appendix A.

As a whole, the most important factor of this system is how much fuel the system is capable of saving. The simulations developed show a dramatic increase in just the efficiency of the on-board generator, up to 2.5 times the energy output in the most beneficial of scenarios. The fuel savings can be seen in Figure 6-11. The figure shows the most fuel savings possible, the low load simulation. In this scenario, after 100 days of consecutive use the hybrid system saves 380 gallons of fuel. In the higher load scenarios the efficiency increase is non-existent. The benefit of the system varies greatly depending on the actual fuel cost.

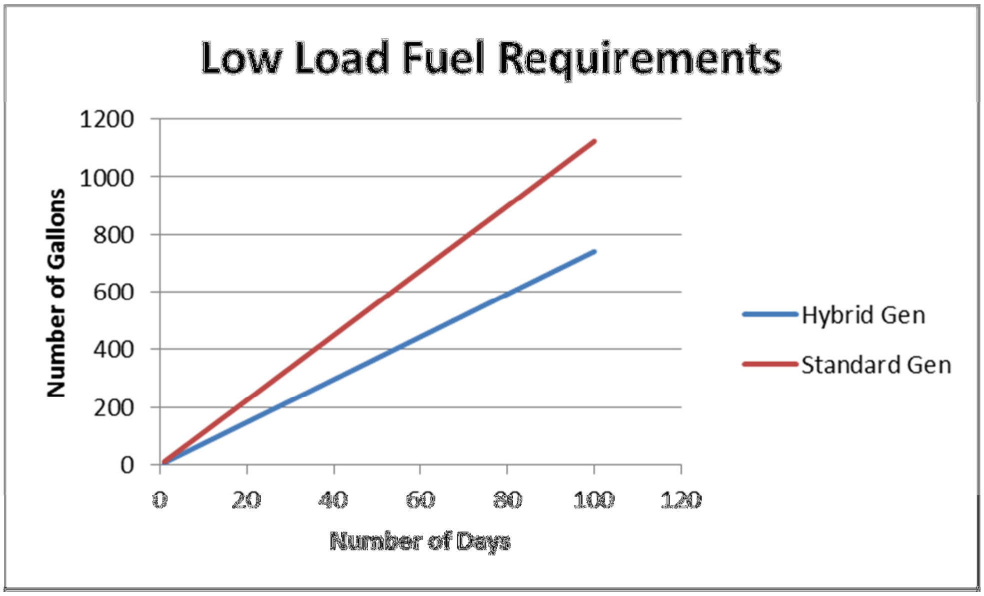


Figure 6-11: Fuel usage comparison hybrid vs. standard low profile. This comparison is over a 100 day span

Table 6-4: Generator simulation efficiencies for both systems. These efficiencies are the 24 hour generator efficiencies for the standard and hybridized generation system, as well as the percentage increase in the system.

Load Profile	Low	High	Varying	Drop-Off	Actual
Standard 24 hour Average Generator Efficiency (%)	15.06	34.96	26.86	13.28	14.52
Hybridized 24 hour Average Generator Efficiency (%)	36.10	36.05	35.85	36.10	36.10
Generator Efficiency Percent Increase (%)	21.04	1.09	8.99	22.82	21.58

The simulation performed for this analysis only compares the direct fuel savings, the fuel put into the system to power the demands at the forward bases. Not in the scope of this project is the indirect fuel savings that the system would be able to create. There are several different ways the system would create indirect fuel savings, as well as create additional indirect fuel requirements. With increased fuel efficiency of the system, less refuel convoys are required thus saving fuel in the transportation of the fuel energy itself. In addition to the fuel savings the reduction in convoys saves, with convoys being the highest casualty reason in current times the system could also saves numerous lives. At the same time, the additional weight of the battery pack requires additional fuel to tow it to the front lines and even fly the system into the theatre to begin with. Though determining these exact numbers was outside the scope for this project, it would be important to review for future research

Chapter 7: Conclusion and Future Work

In this study a mobile hybridized power generation system was designed and simulated. This project has been inspired by the overwhelming cost, in both money and lives, that the armed forces must pay for energy in theatre. Most of the military's forward operating bases obtain/generate power using standard towed-in generators that operate on JP8 fuel. Being this reliant on fossil fuels in the field has left a visible weakness of the system. Not only can the delivered fuel cost upwards of hundreds of dollars a gallon but the refueling convoys are very susceptible to enemy ambushes. In 2007 alone, there were more than 3,000 Army personal and contractors wounded or killed in conflicts that resulted from attacks on fuel and water resupply convoys in just Iraq and Afghanistan. Reducing the necessary number of resupply convoys is one way that both money and lives could possibly be saved.

The goal of the project was to design and simulate a hybridized generation system to both increase on-board generation efficiency as well as be able to obtain and store energy from a variety of scavenged power. With the use of a battery pack several advantages become present in the system. First, the battery pack can add additional load onto the generator and store the additional energy created. This can greatly increase efficiency of the generator system due to generator's characteristic of operating much more efficiently at a higher load. An on-board energy storage system, in addition to increasing the energy generation efficiency, also has the capability to take in energy from a variety of scavenged sources. This aspect allows the system to take advantage of a stable power grid if available. This grants the ability to take a full battery pack worth of energy to the required location before any fuel energy is required. Much like the energy into the system, the use of the battery pack, with corresponding converters and inverters, grants the ability to supply a variety of different outputs depending on the loading situation.

This design process has detailed analysis ranging over the entire design of the project including the energy storage system, power input system, power output system, and the management system for each. The basic design for this system is based on a series hybrid vehicle, without the traction motor. Before any of the individual systems could be designed the overall system requirements must be established. It was determined that a 10kW diesel, or JP8, generator would be sufficient for the energy production requirements using basic FOB requirements as a working point. Also that a 10kW-hr battery pack would be sufficient to meet all of the requirements the hybridized system would present. A variety of possibly energy storage systems were analyzed and a battery chemistry selection equation was developed. For the specifics of our design, a Lithium Iron Phosphate battery pack was selected due to the combination of energy density storage, stability, and cost. This chemistry may not be the best choice for all scenarios, but the selection equation will help determine a suitable choice. Once the battery pack was selected and sized the power generation and input system could be designed.

As stated earlier the power input system can take in several types of energy either from an on-board generation system or from scavenged power. Simulations were developed, on both the standard and hybridized system showing a dramatic increase in just the efficiency of the on-board generator, up to 2.5 times the energy output in the most beneficial of scenarios.

In the system proposed, for safety precautions the system does not generate power from both the on-board generators and the scavenged power simultaneously. A basic control strategy was designed and presented for this as well. The scavenged power input takes advantage of the most common power inputs found: 110 VAC, 24 VDC, and 12 VDC, as well as renewable energy resources the armed forces are strongly pushed towards. The power output system is very similar to the power input system, in that it takes advantage of the battery pack to interact with the most popular outputs. These outputs are the same as the charging inputs, with the addition of 3.3 VDC power supply. The addition of the hybridized system allows for a higher peak output over the standard generation system; however, this output level is not continuous. Because of this, load prioritization and load shedding are required. By monitoring each of the load outputs, in conjunction with a programmable graphical user interface, a load shedding scheme has been developed.

Moving forward with this work would involve continuing on each of the proposed generalized design sections until a completed design can be demonstrated. In addition to completing the design, the design itself can be improved upon in a couple of ways. First of which is to be able to accept power from all of the sources at one time. This would involve additional circuitry that has not been taken into consideration for this project. Also, it has been proposed to run two smaller separate generators to be able to control them separately to further enhance the efficiency profile of the system. More in-depth cost analysis could be completed on several different scales of the system.

As mentioned earlier, equation 3-1 goes into detail about battery chemistry selection. This equation highly depends on importance ratings that have been estimated. The values used need to be validated by official sources.

The military has already invested in several organizations that have looked into hybridized power generation and have completed comparisons for the different possible scales of the systems.[34] The continuation of this project would include more in depth full scale comparison, including non-hybridized aspects of the system. Some of these aspects include, but are not limited to, modularity, scalability, supportability, noise, employed footprint, and manpower burden. Some of the non-hybridized aspects include the indirect fuel savings that could be obtained through transportation causes; both savings of the transportation of fuel to the front lines and the cost of having to initially move more weight to the front lines. Considering such a broad range of factors is something not performed in this work, but is crucial for moving forward.

The result of this design would be an efficient mobile hybridized generation platform that has the ability to accept and supply a variety of power options. While the main focus of this project is for the military there are scenarios that non-military organizations can take advantage of these technologies. The goal of this project, as previously mentioned, is directed at the military forces to help save both money and lives as the cost of fuel continues to increase.

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Appendix A: Simulation Output:

In section 5.4 of this report several simulations were run to determine the effectiveness of the hybridized generation system over the standard generators normally used. This appendix reviews the output that those simulations.

Standard Power Generation

The first thing simulated in section 5.4 is the standard generator set that is normally used to handle a variety of load requirements; the figures in this section have been labeled 1-7.

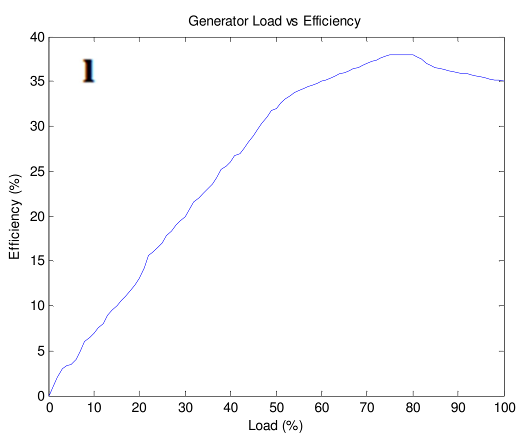
1: This figure shows the standard generator load vs. efficiency used for all of the simulations.

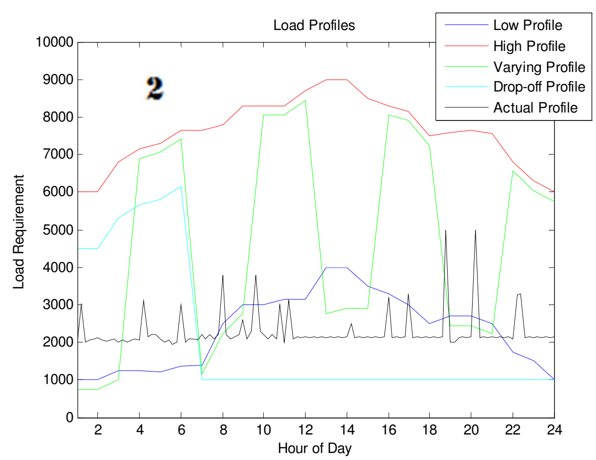
2: This figure shows the load profiles used to compare the different kind of generation systems.

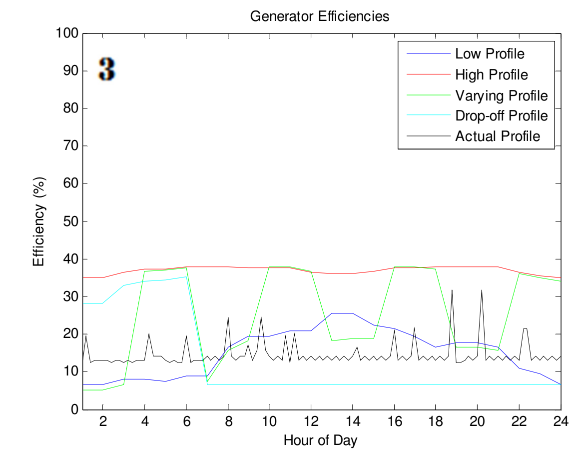
3: This figure shows the generator efficiencies on an instantaneous basis throughout the day.

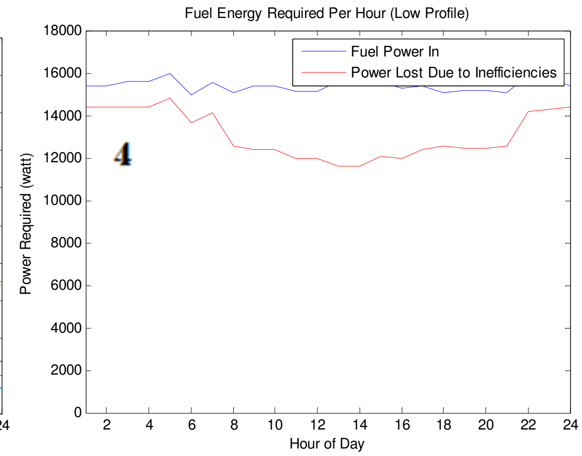
4-7: These figures show the relationship between fuel power in and energy output for all the different profiles. These plots are for the low, high, varying, and drop-off profile respectively.

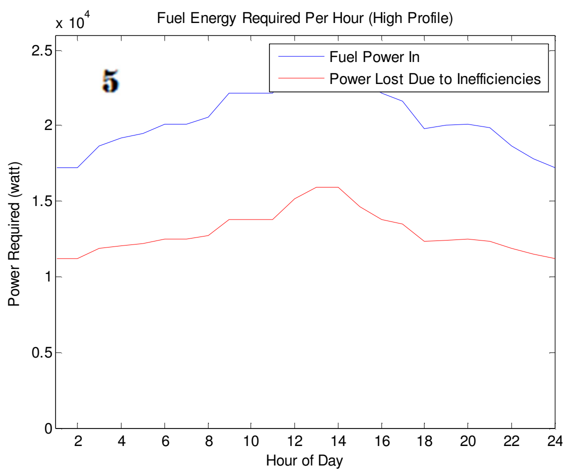
Output:

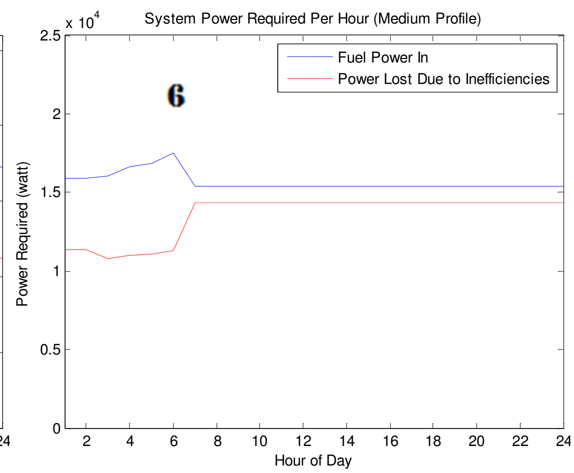


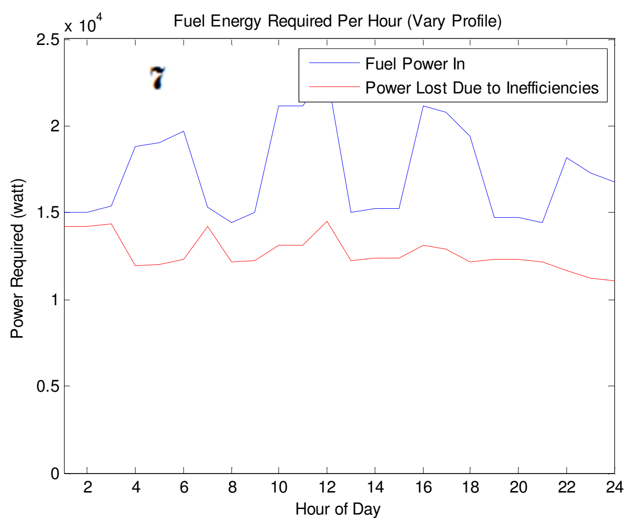



Generator Efficiencies
3
Low Profile
High Profile
Varying Profile
Drop-off Profile
Actual Profile
Efficiency (%)
Hour of Day


Fuel Energy Required Per Hour (Low Profile)
4
Fuel Power In
Power Lost Due to Inefficiencies
Power Required (watt)
Hour of Day


Fuel Energy Required Per Hour (High Profile)
5
x 10^4
Fuel Power In
Power Lost Due to Inefficiencies
Power Required (watt)
Hour of Day

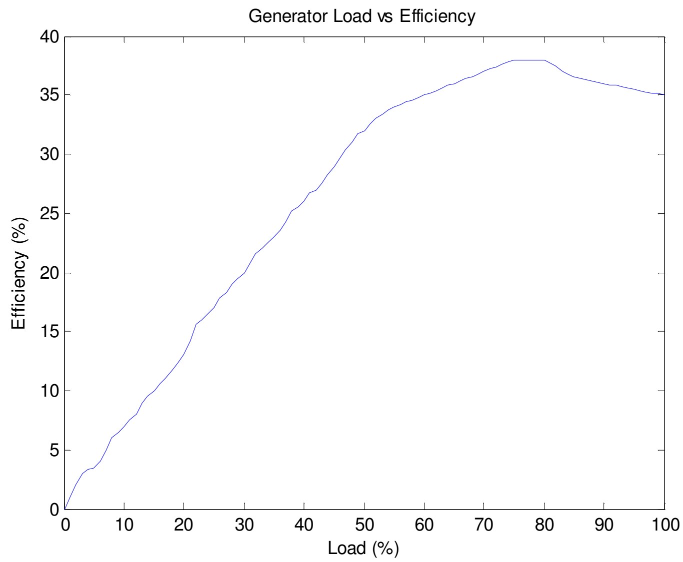

System Power Required Per Hour (Medium Profile)
6
x 10^4
Fuel Power In
Power Lost Due to Inefficiencies
Power Required (watt)
Hour of Day


Fuel Energy Required Per Hour (Vary Profile)
7
x 10^4
Fuel Power In
Power Lost Due to Inefficiencies
Power Required (watt)
Hour of Day

Hybridized Power Generation

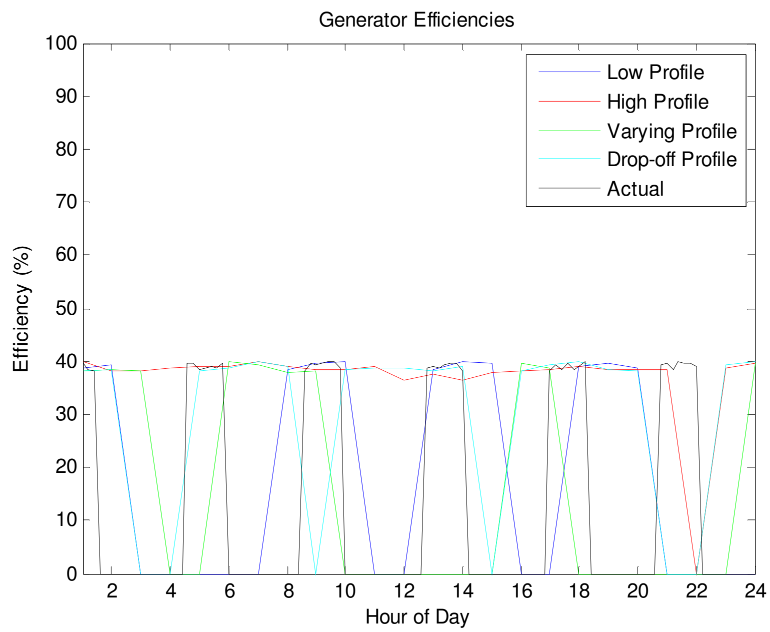
In section 5.4 after the standard generator set had been simulated several different hybrid simulations were performed to show the increase in efficiency possible. The plot below is the same plot used in the standard simulations for the generator load vs. efficiency calculations.

Output:



Starting State Of Charge: 20%

The first hybridized system simulation to be performed was the 20% starting state of charge on the battery pack. The figure below shows the efficiency ratings for all of the profiles. It is important to note that when the efficiency is at zero the generator is off.



Low Profile

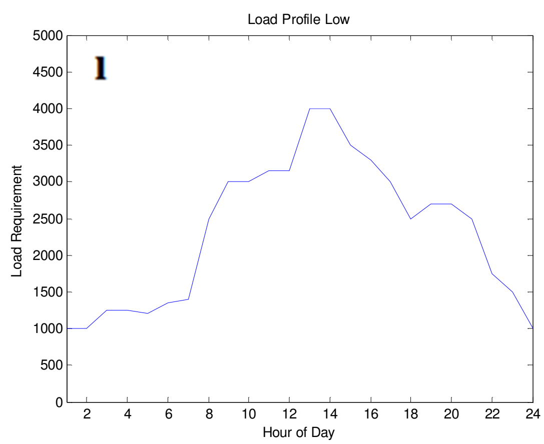
The following figures are the outputs for the simulation that are unique to the low profile with a 20% starting state of charge.

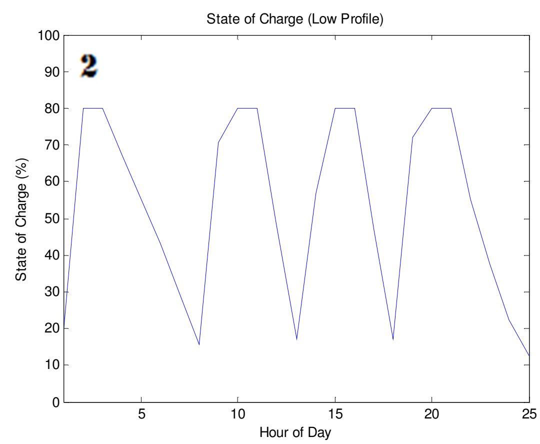
1: This figure shows the load profile used for the simulation, the low load profile.

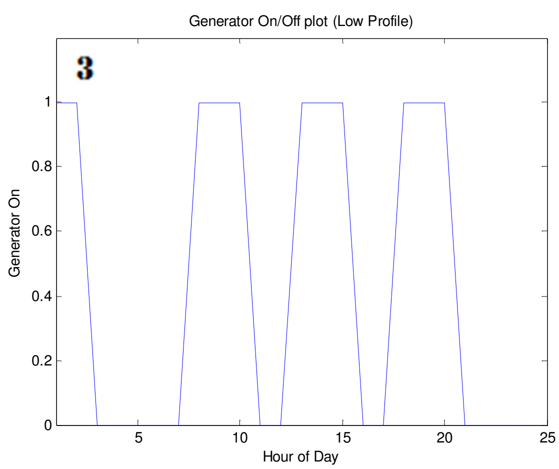
2: This figure shows the tracking of the state of charge for the system. The excess energy generated goes into the battery pack raising the state of charge.

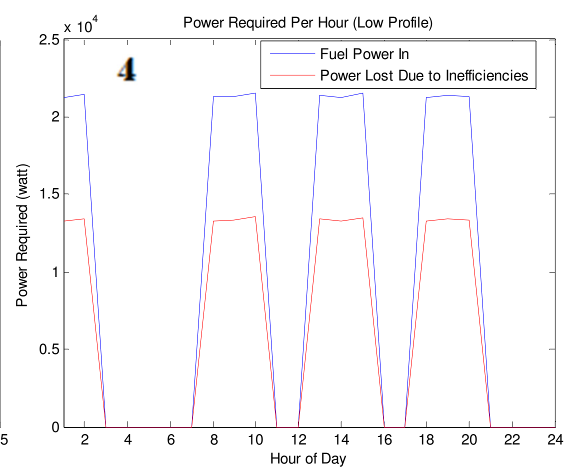
3: This figure shows the relationship between fuel power in and energy output for the low profile.

4: This figure shows the times at which the generator was turned on or off. With the generator off the battery pack supplies the necessary power to the load.









High Profile

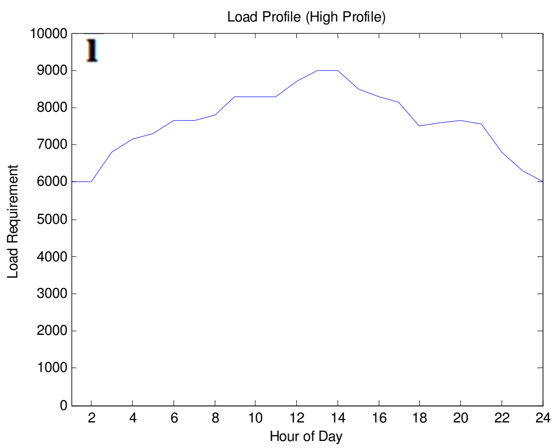
The following figures are the outputs for the simulation that are unique to the high profile with a 20% starting state of charge.

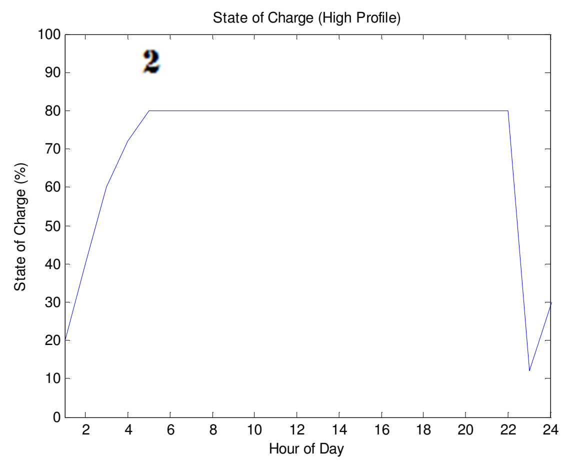
1: This figure shows the load profile used for the simulation, the high load profile.

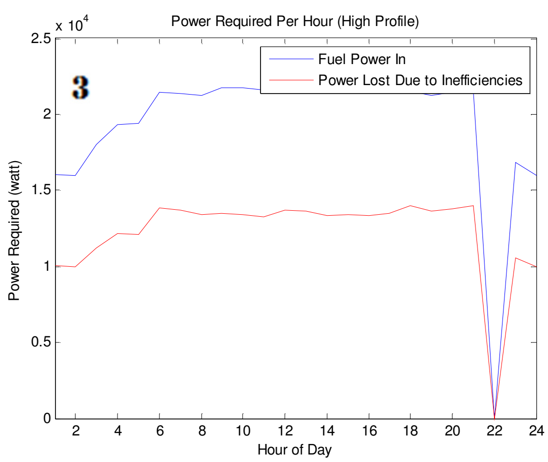
2: This figure shows the tracking of the state of charge for the system. The excess energy generated goes into the battery pack raising the state of charge.

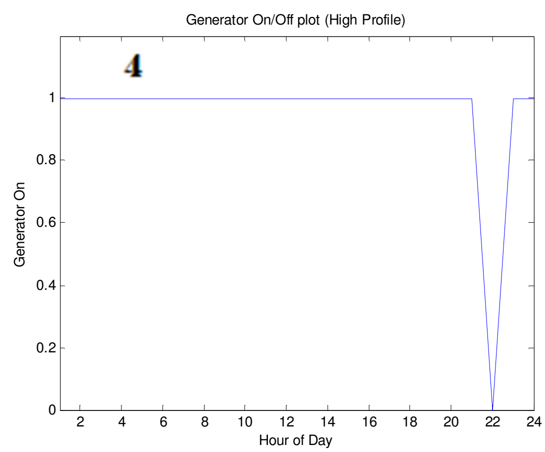
3: This figure shows the relationship between fuel power in and energy output for the high profile.

4: This figure shows the times at which the generator was turned on or off. With a higher profile such as this the generator actually remains on the entire cycle.









Medium/Drop-Off Profile

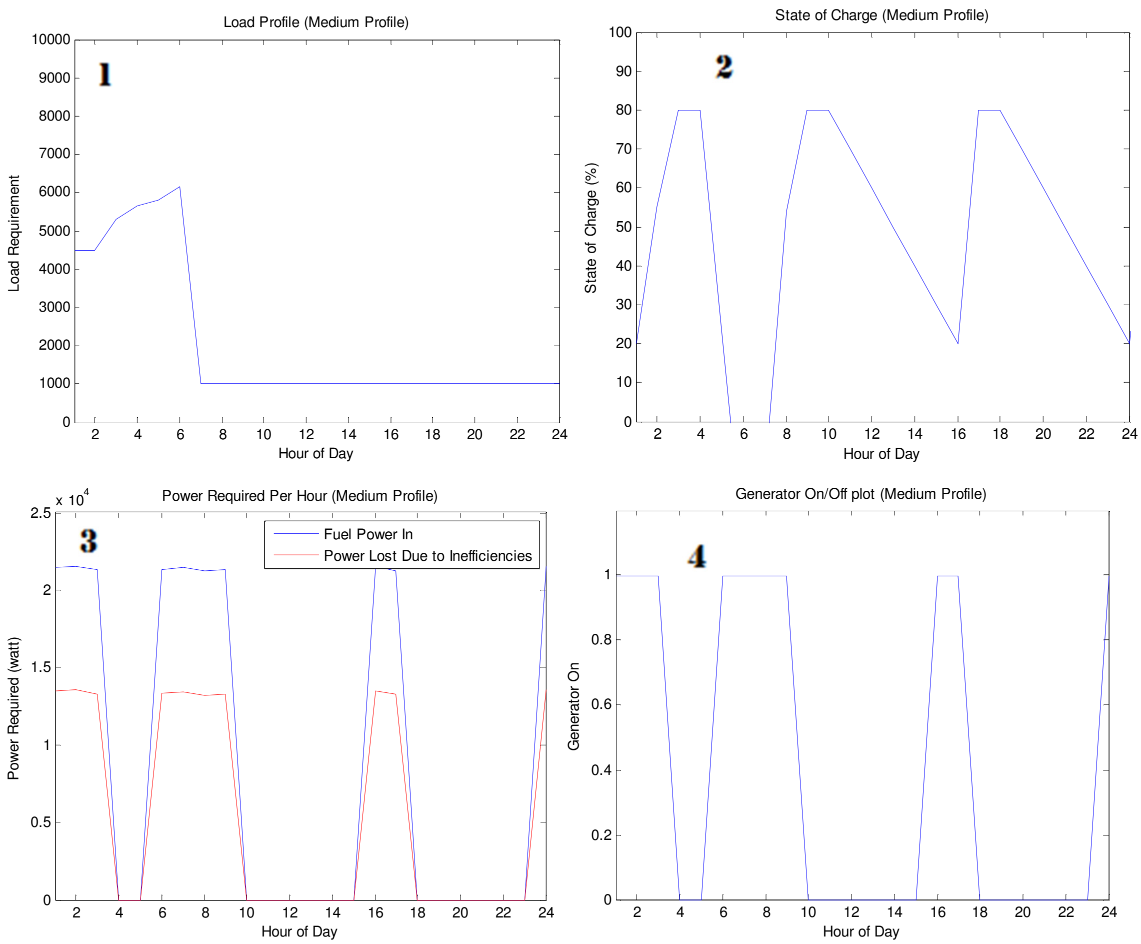
The following figures are the outputs for the simulation that are unique to the medium/drop-off profile with a 20% starting state of charge.

1: This figure shows the load profile used for the simulation, the medium load profile.

2: This figure shows the tracking of the state of charge for the system. The excess energy generated goes into the battery pack raising the state of charge.

3: This figure shows the relationship between fuel power in and energy output for the medium profile.

4: This figure shows the times at which the generator was turned on or off. The generator remains on until a designated higher state of charge is reached.



Varying Profile

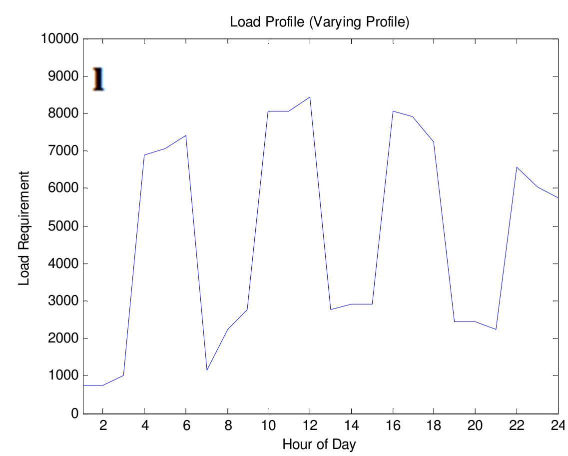
The following figures are the outputs for the simulation that are unique to the varying profile with a 20% starting state of charge.

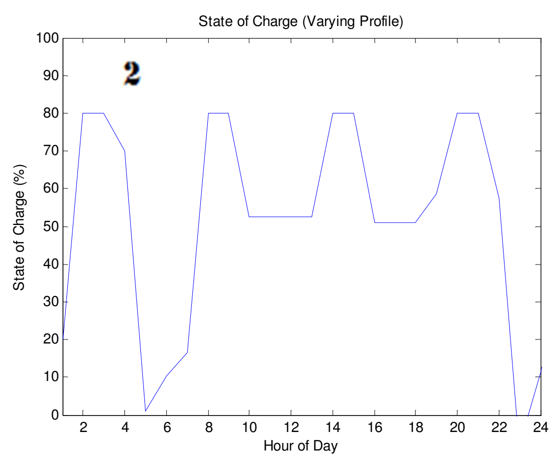
1: This figure shows the load profile used for the simulation, the varying load profile.

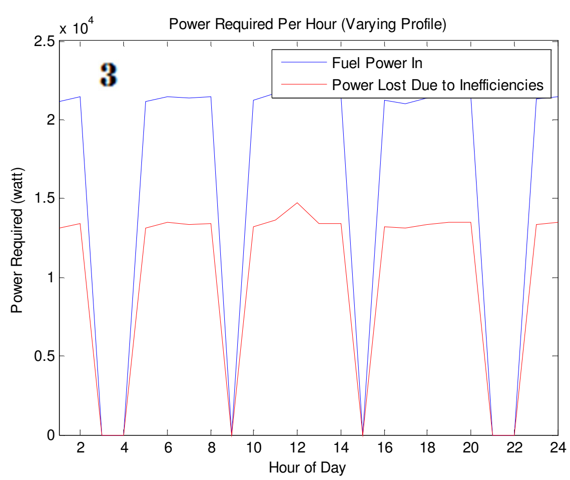
2: This figure shows the tracking of the state of charge for the system. The excess energy generated goes into the battery pack raising the state of charge.

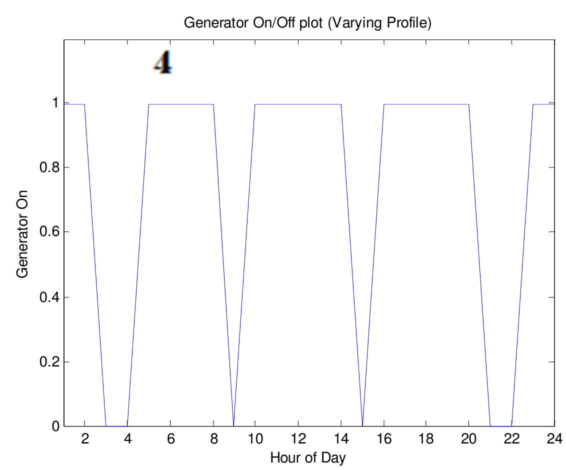
3: This figure shows the relationship between fuel power in and energy output for the varying profile.

4: This figure shows the times at which the generator was turned on or off. The generator remains on until a designated higher state of charge is reached.









Actual Profile

The following figures are the outputs for the simulation that are unique to the actual profile with a 20% starting state of charge.

1: This figure shows the load profile used for the simulation, the varying load profile.

2: This figure shows the tracking of the state of charge for the system. The excess energy generated goes into the battery pack raising the state of charge.

3: This figure shows the relationship between fuel power in and energy output for the varying profile.

4: This figure shows the times at which the generator was turned on or off. The generator remains on until a designated higher state of charge is reached.