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Introduction

The term "power generation" encompasses a wide variety of applications from emergency backup use to prime power and island power and from small units for home use up to large units (1+ megawatts). Prime power or island power generation is used when there is no local electrical grid that can be relied on and one or more generators will be used to provide power for a facility, village, or military base.

Fuel cost is the single largest contributor to lifecycle cost in these island power scenarios as the generator(s) will run 24 hours a day. This cost can be even larger in remote areas where the cost to deliver the fuel can greatly increase the total cost per gallon. In military wartime scenarios, fuel delivery also comes with a significant risk of loss of life. There were an estimated 250 casualties in FY2007 directly related to fuel delivery, equating to one casualty per 24 fuel convoys (Eady, et al., 2009).

Conventional diesel generators provide good fuel efficiency at higher loads. However, efficiency decreases at lower loads (<40%). Unfortunately, generator systems are sized to meet peak power demand, which can result in generators operating significant amount of times at lower load with reduced fuel efficiency. This situation can be even worse in critical facilities where more generators are kept online to provide high power reliability.

Renewable energy, such as solar or wind, can help offset this fuel consumption. However, the potential variability of renewables can sometimes have a surprising counter-effect wherein the generator cannot be downsized yet the renewable energy sources cause the generator to run at even lower loads in regions with even worse fuel efficiency.

Hybridization and electrification are now common in the automotive industry as a means to reduce fuel consumption. However, this approach has only recently begun to be explored for power generation. Czero has developed and tested a hybrid power generation system prototype designed to provide improved fuel efficiency at lower loads that offers 40% fuel savings for typical camp daily load profiles in-theater.

Hybrid Power Generation for Improved Fuel Efficiency and Performance

System Architecture Study

Czero performed a system architecture study prior to beginning detailed design work to look at the benefits and tradeoffs of different design concepts. Four key design attributes were considered:

- Constant vs. variable speed prime mover
- Permanent magnet vs. synchronous generator
- Number of engine-generator sets
- Energy storage

Constant vs. Variable Speed Prime Mover

Conventional generators run at fixed speed (1800RPM for 60Hz, 1500RPM for 50Hz), regardless of the electrical demand. Operating at high speed and low load is not fuel efficient and can cause maintenance issues, such as "wet stacking", where the diesel fuel does not fully combust and begins to accumulate in exhaust system components.

A variable speed engine, however, can be slowed down in response to reduced electrical demand. This allows the engine to operate in regions with better fuel efficiency and with fewer maintenance issues. Figure 1 shows an example of this. In this example, 20HP can be achieved by the engine at high engine speed and low BMEP (and torque) (Point #1) or at low engine speed and high BMEP (Point #2).

However, these points provide very different fuel efficiency. Specific fuel consumption for the higher speed point (#1) is ~400g/kW/hr while the lower speed point (Point #2) is significantly reduced (~220g/kW/hr). Because conventional gensets operate at a fixed speed, they cannot benefit from the improved fuel efficiency that can be obtained by meeting lower load requirements by running at a slower speed.

Fuel Consumption Map [g/kW-Hr]
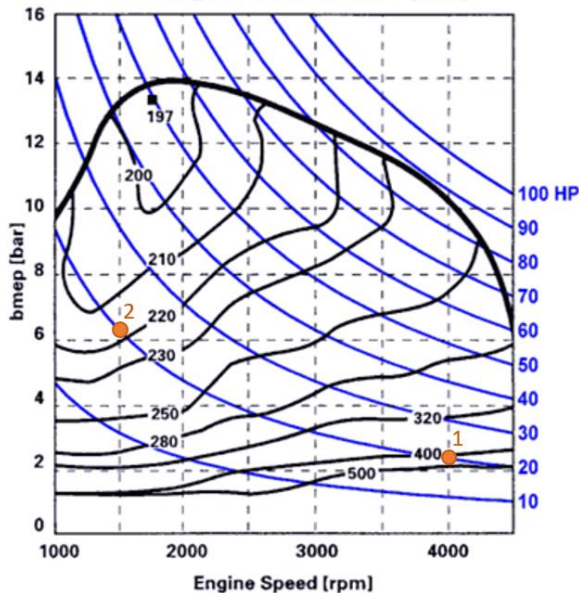B. Georgi, et al., SAE972686 (1997)

Figure 1: Example diesel BSFC map

Two key items must be addressed with variable speed operation. A generator connected to a variable speed engine will produce "wild" AC with varying voltage and frequency. This must be rectified and inverted to produce usable AC power (e.g. 480V, 60Hz). In addition, variable speed engines generally suffer from poor transient response as the engine must be accelerated to meet an increased load demand (Stott, 2010). One method for addressing this is through the addition of energy storage, which is discussed more in the energy storage section below.

Permanent Magnet vs. Synchronous Generator

Synchronous AC generators are the norm for power generation. Synchronous AC generators are readily available at relatively low cost, but efficiency can vary multiple percentage points as the load changes. They are best suited for constant speed operation. These machines are also typically air-cooled, which results in a relatively large footprint to ensure sufficient cooling airflow.

A Permanent Magnet Generator (PMG) uses permanent magnets rather than field coils to generate the magnetic field in the rotor. This allows for much stronger magnetic fields and allows PMGs to be more power dense than synchronous AC generators. Permanent

Magnet Generators are better suited for variable speed operation and can achieve higher, near constant efficiency throughout the load range. PMGs are also typically liquid-cooled, which further reduces the footprint compared to synchronous machines. As such, PMGs combined with variable speed prime movers offer potential for improved efficiency in a smaller footprint than conventional generators. However, PMGs are not as readily available as synchronous AC generators and are more expensive due to the use of rare earth magnets.
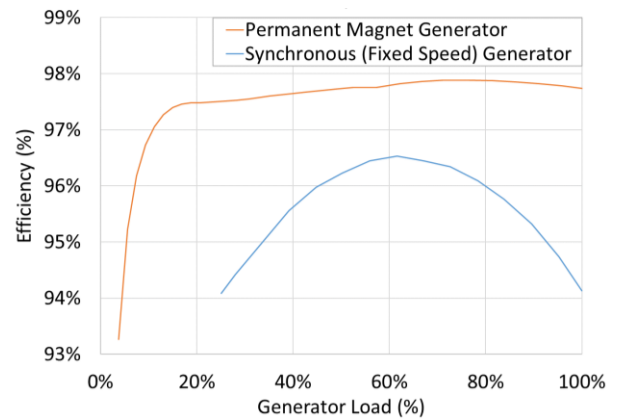

Figure 2: Generator efficiency comparison

Number of Engine-Generator Sets

Incorporating multiple smaller engine-generator sets can also reduce fuel consumption and maintenance issues at lower system loads. This is done by operating only as many engine-generators sets as needed to support the load, thus putting a higher load on each individual engine. System architectures ranging from one to four engine-generator were considered for the hybrid power system.

Using multiple engine-generators reduces fuel consumption at lower system loads. For fixed speed engine-generator sets, two to four sets produced near constant specific fuel consumption down to 20% load. Increasing the number of generator sets continued to improve specific fuel consumption below 20% load, as shown in Figure 3.
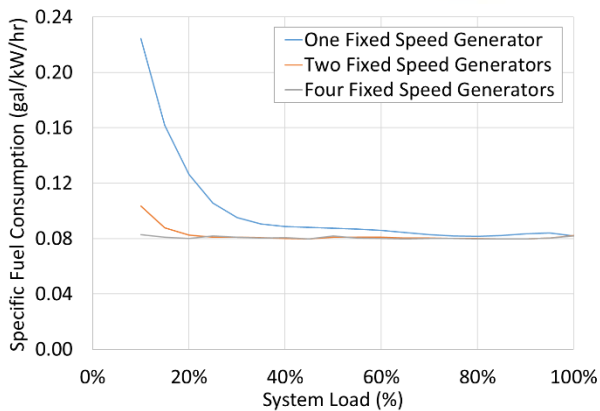
Figure 3: Fuel consumption variation for multiple fixed speed generators

With variable speed engine-generator sets, the fuel consumption at lower loads for a single unit is already greatly improved compared to a fixed speed engine-generator (as discussed previously). As such, the relative improvement with increasing number of units is reduced. Two to four variable speed engine-generator sets offer similar fuel consumption across all loads, as shown below.
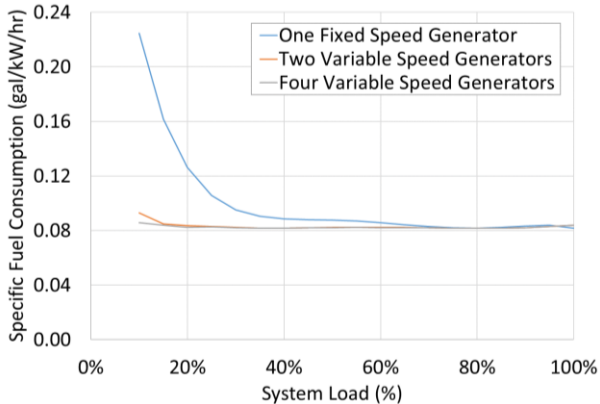
Figure 4: Fuel consumption variation for multiple variable speed generators

Energy Storage

Energy storage can be used in a wide variety of ways in a hybrid power system. Each use has different benefits but also creates different requirements for the system that must be considered. In addition, there are a number of energy storage technologies available with different performance characteristics and one technology may be better suited for a particular use than another. As such, several energy storage use cases were first identified and evaluated as part of the design.

Then, different energy storage technologies were evaluated against these use cases.

The following use cases were identified and evaluated for energy storage in the system:

1. Silent hours operation and Uninterruptable Power Supply (UPS) operation (energy storage only, no engines used)

2. Load leveling/shifting

3. Peak shaving and step load change capability

While silent hours or UPS operation may be desirable capabilities of the system, they do not directly provide any fuel savings. In addition, if energy storage is required for other capabilities (such as peak shaving), the system design and control must ensure that sufficient energy storage is reserved to meet these requirements. While any energy storage technology will allow for silent hours operation, more energy dense technologies are best suited for this requirement as they can provide longer run times for a given volume of energy storage.

Load leveling or shifting generally refers to charging the energy storage during periods of lighter load and discharging this energy during higher load periods to augment the generation. Generally, this is performed on a daily cycle. If the load profile is known a priori and enough energy storage can be incorporated into the design, it is possible to use load leveling to enable downsizing the engine-generator(s), meeting peak demand with a combination of generation and energy storage. However, this results in a time limitation on peak power output. This approach was deemed unacceptable for deployable power generation as the load profile is not known ahead of time and may vary significantly across different applications.

Peak shaving can be implemented at several different timescales. At longer, daily timescales, peak shaving is similar to load leveling, but with reduced capacity as shown in Figure 5.
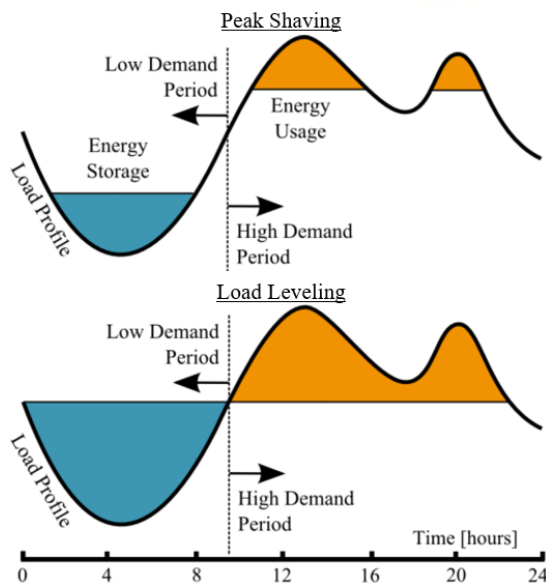
Figure 5: Peak shaving vs. load leveling (Sabihuddin, et al., 2014)

However, peak shaving can also be used on shorter timescales. Particularly when multiple engine-generator sets are employed, energy storage can be used for peak shaving to meet short term load demand without the need to start an additional engine-generator. This can improve fuel economy by keeping generators at higher load and also reduces wear and tear and associated maintenance by reducing the number of engine starts.

The key performance issue noted when using variable speed engines for power generation is poor load response (Stott, 2010). This is due to the time and engine torque required to accelerate the engine to a higher speed to support the increased load. Load response can also be an issue if multiple engine-generator sets are used due to the time required to bring the next unit online. As such, architectures with variable speed engines and/or with multiple engine-generator sets require a certain amount of stored energy that can be supplied at sufficient power levels in order to meet the system step load requirements. The time required for an engine to increase speed is on the order of 1-10 seconds while the time required to bring an additional unit online may be on the order of 30-120 seconds.

Because of the benefits of running variable speed and with multiple units described previously, peak shaving

and step load response became key use cases for the energy storage. As such, preference was given to chemistries with high power density such that the power output required for these cases could be provided in a compact, space efficient package. This quickly eliminated Lead Acid and other low power density chemistries, such as Sodium Nickel Chloride.

Ultracapacitors were investigated for their high discharge rates, however the time scale required for the power discharge to meet system requirements (e.g. 30-120 seconds) would require a significant number of parallel strings of ultracapacitors to provide the required energy due to their extremely low energy density. This was deemed to not be a cost-effective approach in this application.

As such, the focus quickly narrowed to Lithium chemistries. Three chemistries were investigated for their performance characteristics and availability from reputable suppliers: Lithium Titanate (LTO), Lithium Nickel Manganese Cobalt Oxide (NMC), and Lithium Iron Phosphate (LiFePO4). All three chemistries can meet the power and energy requirements for the key use cases identified in a compact package.

LTO chemistry offers the highest peak discharge rates, which initially made it a very attractive option. However, LTO has a high cost premium compared to the other two options. Lithium NMC and LiFePO4 have similar performance characteristics at similar costs. LiFePO4 was selected for this application based on commercial factors.

Design and Engineering

Based on the system architecture trade study, the selected architecture uses two variable speed engine-generator units as this provides the same fuel efficiency benefits as architectures with more units and results in a simpler system and reduced capital cost.

A simplified, high level diagram of the selected system architecture is shown below. The architecture uses two variable speed engine-generator units as this provides the same fuel efficiency benefits as architectures with more units and results in a simpler system and reduced capital cost. The output from the two generators is

rectified and then joined on a DC bus with the energy storage before inverting to AC output.
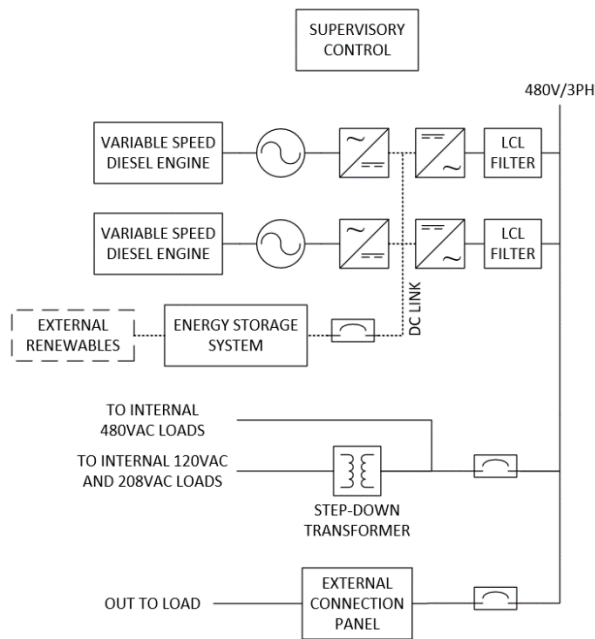
Figure 6: Simplified high-level system architecture

Electrical Design

The power subsystem is at the core of the design. The system architecture shown previously was further developed based on collaboration with key vendors and partners based on specific hardware capabilities.

Transformerless inversion to 480VAC requires a DC voltage of 725V or higher. However, the inverters selected have a maximum DC voltage limit of 800V. This would result in a range of only 75V for the energy storage to operate if placed directly on the DC bus. It was determined that this would drastically reduce the usable energy from the batteries.

As such, a DC/DC converter was added to extract as much usable energy from the energy storage as possible. This also allows the battery voltage to be lower than the DC bus and allows for a larger change in voltage in the batteries, as the DC/DC converter will boost the voltage to the desired voltage of 750V. The DC/DC converter has a high efficiency (~99%), which introduces only minimal losses for power flow into and out of the energy storage.

For the energy storage system, pre-certified, factory tested battery modules were used rather than building a custom pack from the cell level. This greatly reduced the development required while ensuring a robust, safe design. The design team partnered with CIE Solutions for proprietary packaging and energy storage system integration to suit the design. The system can incorporate 110kWh up to 220 kWh of usable energy storage for different applications.

The system uses a proprietary supervisory control system. Off the shelf hardware was chosen based on capabilities and system inputs and outputs required. This was packaged into a custom enclosure for improved maintenance and quality control. This approach offers reduced cost compared to a custom hardware solution. Software algorithms were developed for monitoring and controlling the system. These can be broken into categories:

1. Monitoring and safety

2. System start-up and shutdown

3. Power delivery and management

Algorithms developed to-date use pre-defined logic, not learning or adaptive algorithms. Further development to implement adaptive algorithms is expected to provide even further versatility and fuel economy benefits over the existing implementation.

The final electrical architecture is shown in Figure 7. This system is expected to be able to provide 800kW/1000KVA power output from a compact, deployable package.
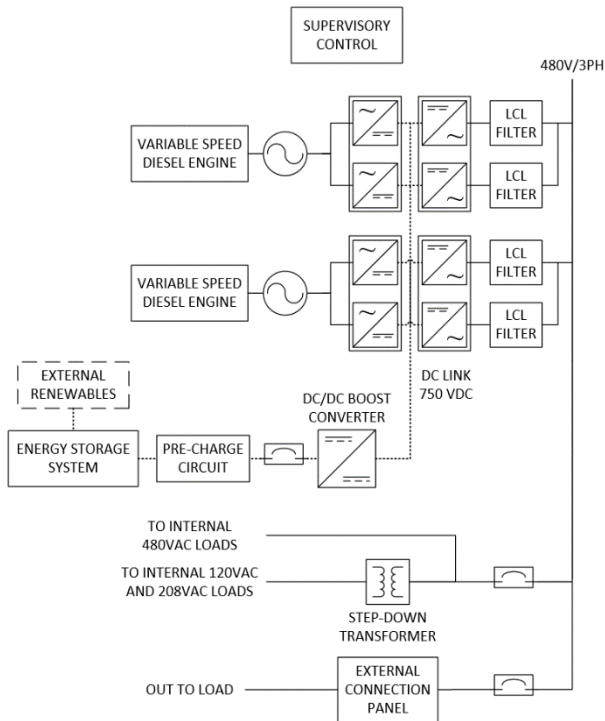
Figure 7: Final high-level system architecture

Mechanical Design

The mechanical design was divided into three interrelated areas:

1. Power Module

2. Electrical packaging

3. Overall mechanical structure

Design in these areas occurred in parallel and in close collaboration with multiple design iteration loops to meet the demanding packaging constraints of the system. The overall mechanical structure design and analysis will not be covered in this paper.

The Power Module consists of:

1. One variable speed engine-generator unit

2. One Energy Storage Module, which contains half of the total system energy storage

3. Related subsystems (e.g. cooling)

There are two Power Modules in the current design, though the architecture is extensible from one to many Power Modules.

The Power Module was designed with a Tier 4 Final engine to provide compliance with latest emissions standards. Compact packaging was essential to meet the space constraints of the design, but the design still ensures access to key maintenance items. The Energy Storage Module is a sealed, temperature-controlled environment designed to be factory-serviced to prevent access and maintenance by untrained personnel.

There are multiple cooling subsystems in the Power Module. The engine and related components are cooled with an engine driven water pump, as with conventional engine-generators. The engine radiator and charge air cooler are cooled with an engine driven fan. Liquid cooled electrical components are cooled with an electrically driven pump and separate radiator cooled with VFD controlled fans to limit parasitic loads. The energy storage is air-cooled with a purpose-built integrated air conditioning unit.
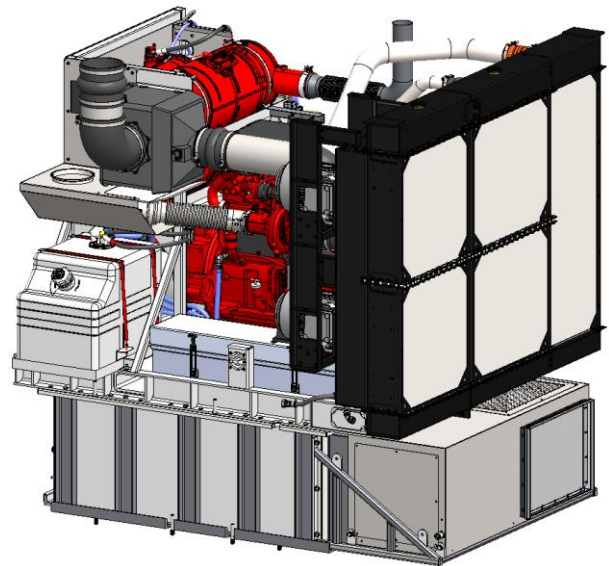

**Figure 8: Left view of Power Module and cooling system**
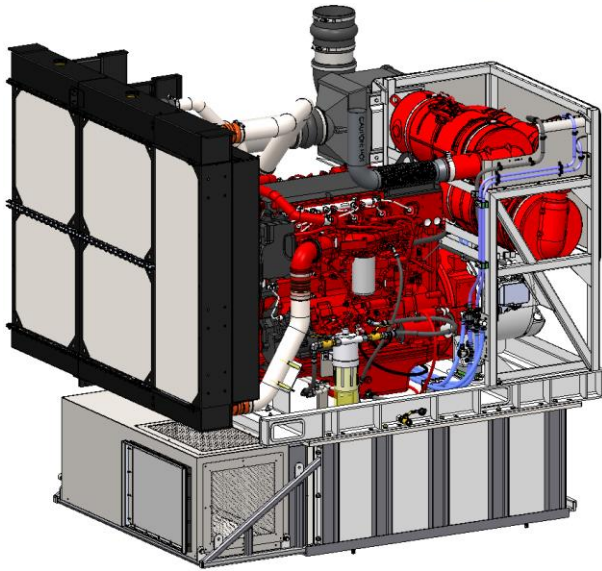
Figure 9: Right view of Power Module and cooling system

CFD was performed using ANSYS Fluent to study the airflow over radiators and through the engine compartment area to confirm sufficient cooling given the tight space constraints and high ambient operating temperatures. Initial results were used to influence mechanical structure design to optimize airflow. Figure 10 and Figure 11 show air temperature in the engine compartment. Some hotspots can be seen, particularly on the Diesel Particulate Filter behind the engine, but all temperatures are within component specifications.
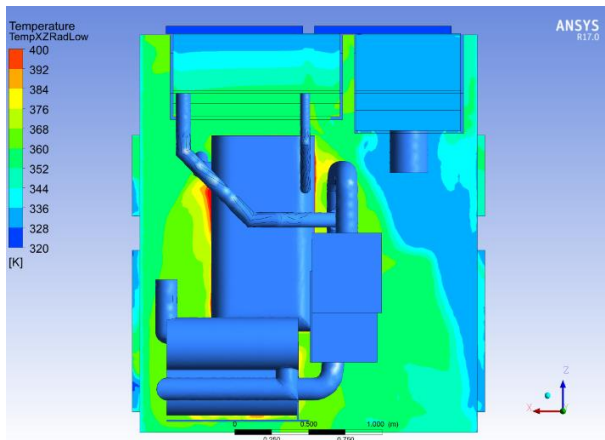

Figure 10: CFD results from engine compartment (top view)
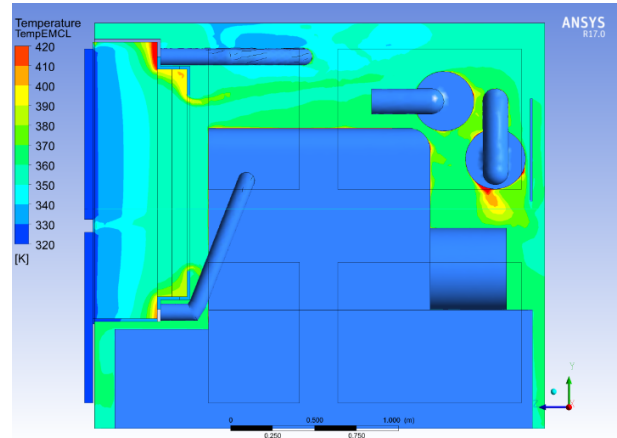
Figure 11: CFD results from engine compartment (side view)

CFD was also performed on the cooling airflow within the Energy Storage Module. The compact packaging required introduced a risk of poor airflow distribution and regions with insufficient cooling. Compact plenums on both sides of the energy storage were designed to create even pressure distribution to help provide relatively uniform flow throughout the system. Figure 12 shows air velocities through the cooling passages. The flow is not perfectly uniform but is sufficient to prevent any localized hot spots.
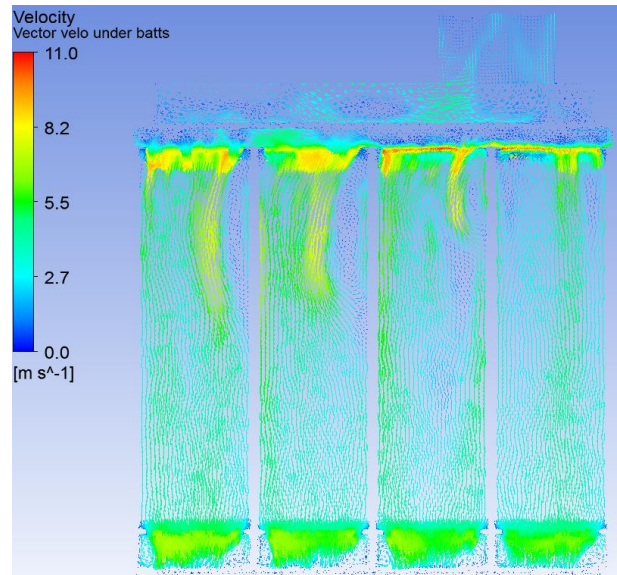
**Figure 12: CFD results from Energy Storage Module**

The hybrid system architecture results in additional electrical equipment beyond that found in conventional generator units. This, coupled with the goal of

maximizing power density while still achieving maintainability and power resiliency, created challenges with respect to the packaging of the electrical equipment as very limited space was available for this equipment.

This electrical section is divided into two areas for power electronics and for control equipment and support subsystems. Packaging challenges for the power electronics were primarily due to the size of the equipment, large power cables with limited bend radii, and hoses required for liquid.

The key challenge for control equipment and support subsystems was accessibility for maintenance given the limited space available. It was important to keep all breakers readily accessible while also allowing for access to other equipment that may need to be replaced over time. A hinged panel system was designed that allows easy access to breakers will still providing access to equipment packaged behind the breakers. The HMI is housed in this area but is accessed from outside the structure via a separate panel.
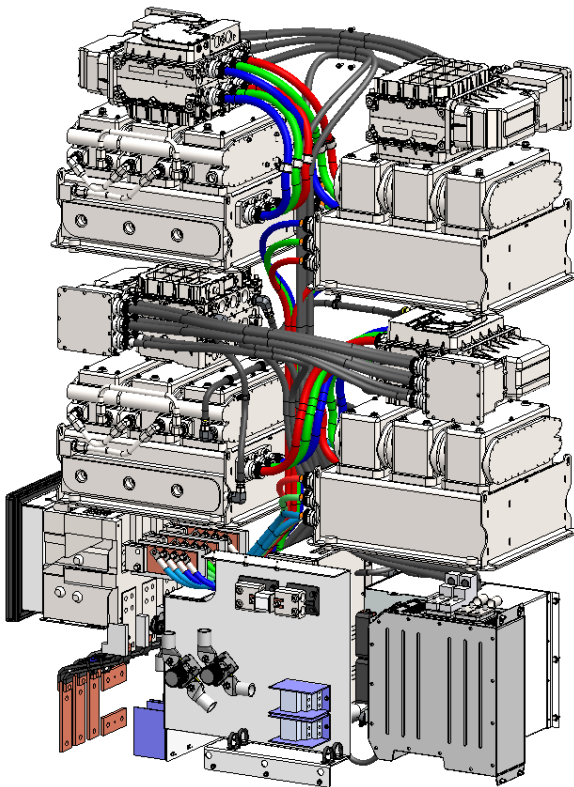

Figure 13: Compact packaging of electrical equipment

Prototype Test Results

A partial system with one engine-generator was built for testing to prove the concepts and benefits of the design. The Test System architecture is shown in Figure 14.

The focus to-date has been on functional and preliminary performance testing. The test results below demonstrate variable speed operation with power output from 5kW to over 400kW. The results also demonstrate the energy storage providing step load response while the variable speed engine responds on a slower timescale.
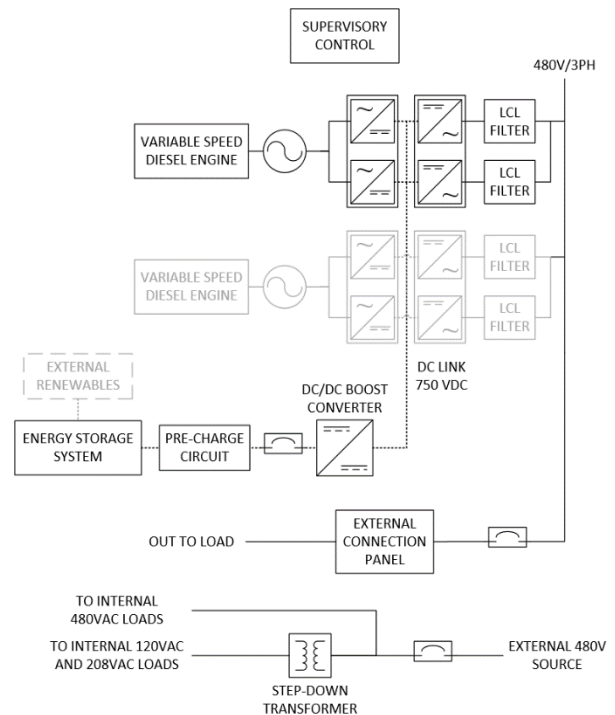
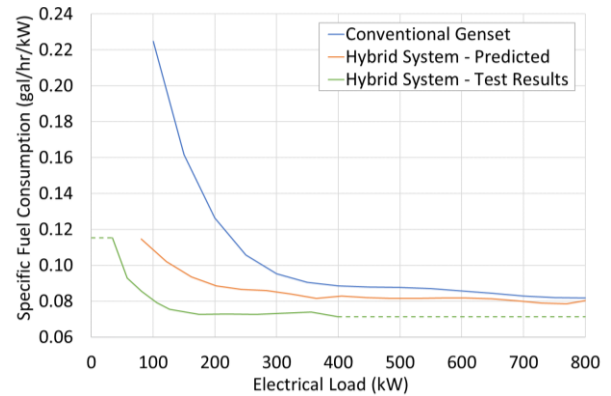**Figure 14: Test system architecture**
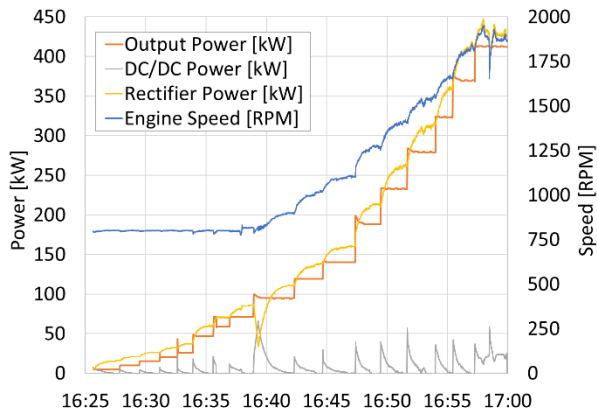
Figure 15: Test results from power ramp up to full load

Figure 16: Fuel consumption test results

Fuel consumption results from testing, shown in Figure 16 in green, exceed the efficiency estimated during preliminary analyses. This is due to three primary factors:

1. Lower engine BSFC than originally estimated

2. Lower parasitic internal loads than originally estimated

3. Higher PMG efficiency than originally estimated

Expected behavior for the full system has been extrapolated and is shown with the dashed green line. At very low loads, the system will run off battery power only to maintain system efficiency. Test results show >60% reduction in fuel consumption at 100kW and >40% reduction in fuel consumption at 200kW compared to a standard diesel genset. This reduction is expected to provide large fuel cost savings for generators that run a significant number of hours, particularly in remote locations where total delivered fuel cost may be substantially increased.

Step load testing is ongoing and has demonstrated up to 35% single-step changes. Software changes have been identified to enable the system to meet the 50% single-step target. No hardware changes are expected to achieve this.

Conclusion

Several project goals were identified at the start of development. A number of these have been achieved and proven during testing, specifically:

1. Significant reductions in fuel consumption at lower loads compared to conventional diesel generators.

2. Fuel consumption at higher loads that is better than conventional diesel generators.

This performance will result in significant reductions in fuel used and significant associated cost savings – 40% fuel savings for typical camp daily load profiles in-theater.

Two key areas have not yet been proven. Step load performance does not currently meet the 50% single step target but is expected to by the completion of the current testing program. In addition, high ambient temperature performance has not yet been confirmed.

How Czero Can Help You

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Czero develops innovations for the automotive, defense, oil and gas, renewable energy, and clean technology industries.

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- Energy conversion, efficiency, and recovery
- High-bandwidth hydraulics
- Automotive powertrains
- Heavy-duty trucks
- Fuel systems
- Valve systems
- Hybrid vehicles

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James Kersey is technical project lead at Czero in Fort Collins, Colorado. His focus is on technical leadership and management of advanced engineering research and product development programs and has significant experience in automotive, military, and offshore oil and gas applications. He has a BS and MS in Aerospace Engineering from the University of Illinois at Urbana-Champaign. While at the University of Illinois, he conducted research on high speed multiphase flow phenomena, including studies of shock propagation and attenuation in multiphase media.