Hybrid Power Generation for Improved Fuel Efficiency and Performance

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Abstract- **This paper provides an overview of the analysis and design of a hybrid power system, including trade studies and analyses performed to define the system architecture and the performance and fuel economy benefits (predicted and test results) of the system. This system provides a new approach to deployable power generation to overcome key weaknesses of conventional diesel power generation. The hybrid system architecture developed improves lower load performance and fuel efficiency while maintaining similar fuel efficiencies to conventional diesel generators at higher loads. Test results have demonstrated fuel efficiency improvements of greater than 40% at low loads and greater than 60% at very low loads. Furthermore, the system architecture supports renewable energy inputs from sources such as solar and wind, which can further increase overall energy efficiency.**

Keywords- **Hybrid power; energy efficiency; lithium iron phosphate**

I. Background and Motivation

Fuel cost is the largest single contributor to lifecycle cost for power generation in island power scenarios. This cost is amplified in remote areas where the cost to deliver the fuel can greatly increase the total (delivered) cost per gallon. In military wartime scenarios, fuel delivery also comes with a risk of loss of life. The Army Environmental Policy Institute estimated one casualty per 24 fuel convoys in FY2007. In that year alone, there were over 6,000 fuel convoys between Iraq and Afghanistan, equating to 250 casualties directly related to fuel delivery that year [1].

Conventional diesel generators have good fuel efficiency at higher loads. However, specific fuel consumption increases for loads less than 40%, as shown in Fig. 1. Because generator systems for island power are traditionally sized to meet peak power demand, small island power installations may operate significant amounts of time at loads less than 40%, resulting in increased fuel consumption. Even in larger installations, power reliability requirements for critical facilities may require significant spinning reserve, thus, further reducing average generator load and forcing engines to operate in areas of lower fuel efficiency. Running at low loads can also increase maintenance costs due to a condition called “wet stacking,” where the diesel fuel does not fully combust and begins to accumulate in exhaust system components.

Renewable energy sources can provide a means to reduce fuel consumption. However, the potential variability of renewables can sometimes have a counterproductive effect, where the generator cannot be downsized yet the renewable energy sources further decrease the load on the generator. This can cause an unexpected increase in fuel consumption. Micro-grid systems and hybrid power generation systems that also incorporate energy storage can mitigate this issue [2]. Such systems available today are made up of multiple separate components rather than a single, self-contained system. While this may not be an issue for permanent installations, it limits the deployability of these systems for temporary installations.

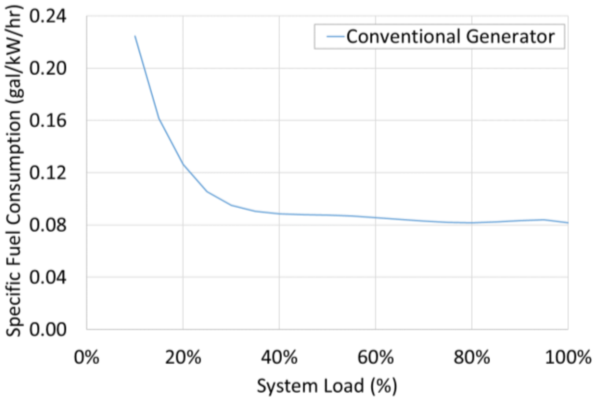

Fig. 1. Specific fuel consumption for a typical conventional diesel-powered generator.

Based on the above and additional commercial and technical factors, the key goals were to:

1. Significantly improve specific fuel consumption over conventional diesel generators at lower loads
2. Maintain efficiency similar to conventional diesel generators at higher loads
3. Maximize power output within a compact, deployable package
4. Support 50% single-step load changes
5. Support operation in high-temperature, desert environment, with minimal to no derating.

II. Analysis-Led Design Process

A systems engineering process incorporating analysis-led design and extensive modeling was used for this development. Key design tensions were identified early between power output, thermal management, and space constraints. Thermal management is critical to reliable operation in desert environments. However, maximizing power output within the fixed space constraints requires making use of all available space. These competing requirements required careful analysis during the design process. The following summarizes the analysis performed and tools used in the development.

1. ANSYS Fluent was used for thermal and airflow modeling in two areas:
    a. Air flow and heat distribution throughout the engine compartment – through inlet louvers and radiators, over the engine and aftertreatment components, through the outlet louvers
    b. Air conditioning flow distribution and heat transfer within the energy storage system.
2. ANSYS Mechanical FEA was used for stress modeling of the mechanical structure to ensure the system met all applicable transportation requirements.
3. Dynamic modeling of liquid cooling circuits was performed in Simulink to inform cooling circuit layout and ensure sufficient coolant flow distribution.
4. SolidWorks was used for component and system design, component FEA, and preliminary mechanical structure FEA.

III. System Architecture Design and Analysis

System level design and analysis was performed prior to detailed engineering to define the architecture best suited to the system requirements. Four key design attributes were considered:

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

A. Constant vs. Variable Speed Prime Mover

Conventional generators run at fixed speed (i.e., 1800RPM for 60 Hz, 1500RPM for 50 Hz), 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, as previously discussed. 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. While Fig. 2 is for an automotive application, the same trends hold true in diesel power generation applications.

Low loads can be met in multiple ways. In the example below, 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 high 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 at lower loads that can be obtained by running at a slower speed.

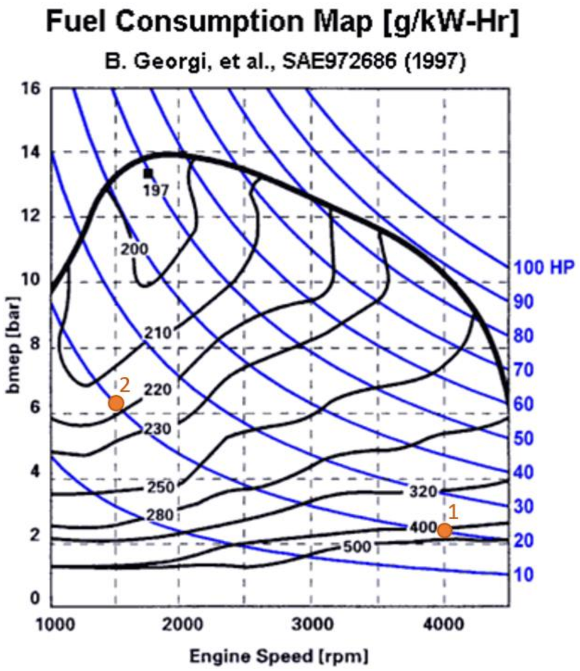

Fig. 2. Example diesel BSFC map [3].

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, 60 Hz). In addition, variable speed engines generally suffer from poor transient response as the engine must be accelerated to meet an increased load demand [4]. One method for addressing this is through the addition of energy storage, which is discussed more in the energy storage section below.

B. 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. PMGs 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, as shown in Fig. 3. However, PMGs are not as readily available as synchronous AC generators and are more expensive due to the use of rare earth magnets.

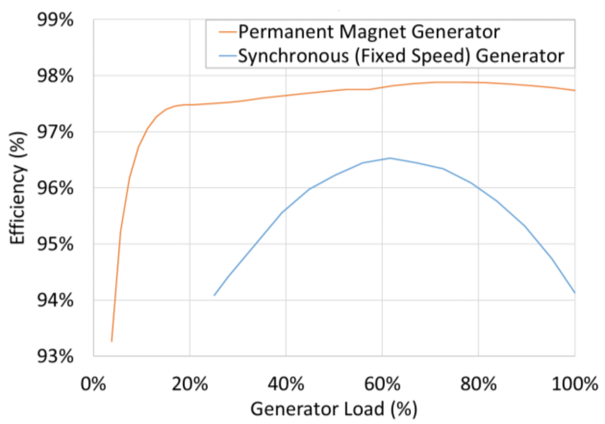

Fig. 3. Generator efficiency comparison.

C. 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 Fig. 4.

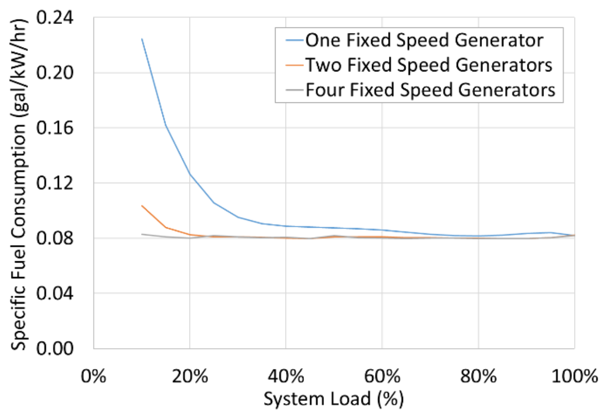

Fig. 4. Fuel consumption variation for multiple fixed speed generators.

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.

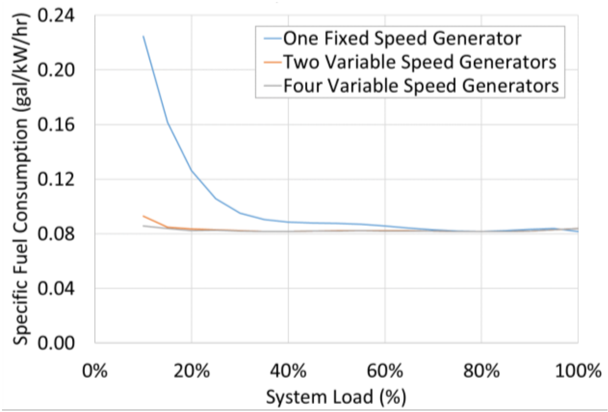

Fig. 5. Fuel consumption variation for multiple variable speed generators.

D. 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.

1) Energy Storage 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 (i.e., 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 Fig. 6.

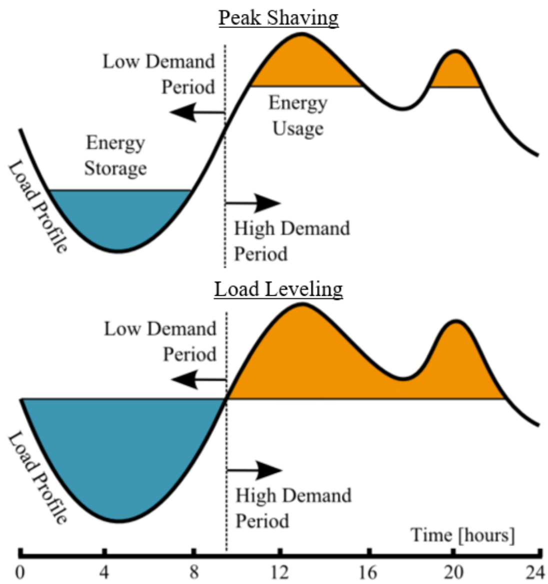

Fig. 6. Peak shaving vs. load leveling [5].

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 [4]. 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 to 10 seconds, while the time required to bring an additional unit online may be on the order of 30 to 120 seconds.

2) Energy Storage Chemistries/Technologies: 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 so 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 to 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.

E. Overall System Architecture

A system architecture was finalized based on the above analysis. Variable speed architectures using PMGs provide significant efficiency improvements at lower load and also offer increased power density compared to designs incorporating synchronous AC generators. This was a key goal for the project.

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.

A simplified, high-level diagram of the selected system architecture is shown below. The output from the two generators is rectified; and then joined on a DC bus with the energy storage before inverting to AC output.

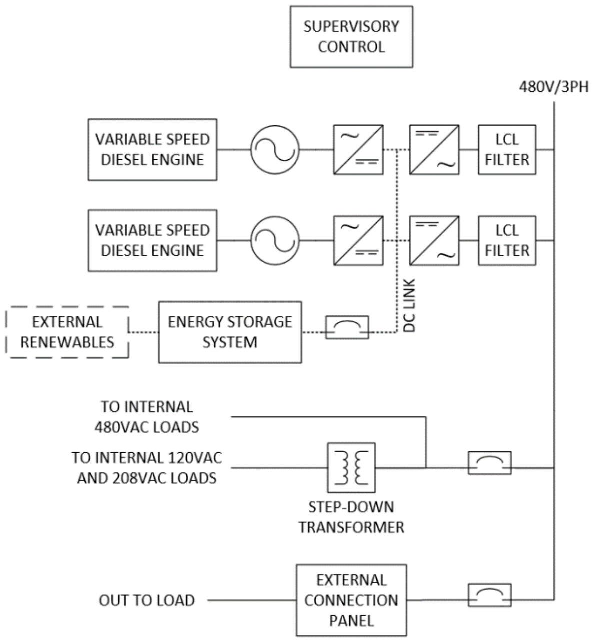

Fig. 7. Simplified high-level system architecture.

III. Electrical Design

The electrical system design was divided into two areas:

1. Power subsystem, including generator, energy storage, and power electronics
2. Support subsystems, including power distribution to internal loads and supervisory control.

Design of the support subsystems will not be covered here.

The power subsystem is at the core of the design. The system architecture shown previously was further developed on collaboration with key vendors and partners 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, precertified, 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 to 220 kWh of usable energy storage for different applications.

The system uses a proprietary supervisory control system. Off-the-shelf hardware was chosen 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 Fig. 8. This system is expected to be able to provide 800kW/1000KVA power output from a compact, deployable package.

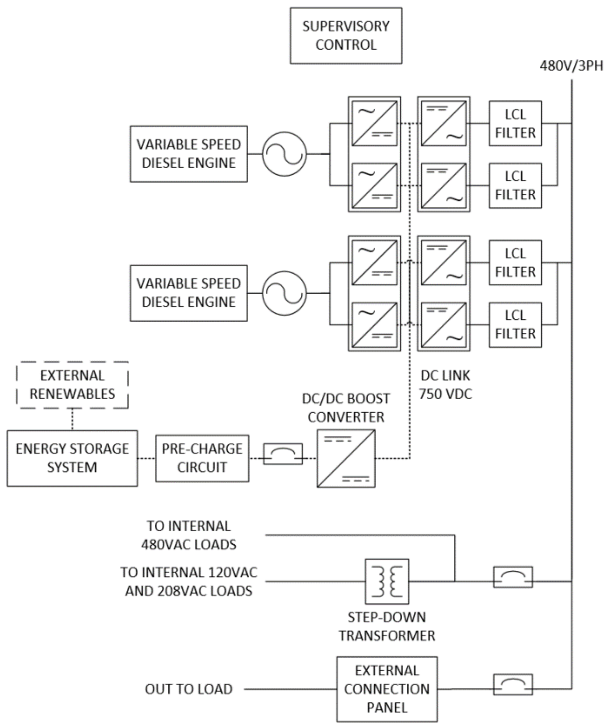

Fig. 8. Final high-level system architecture.

IV. 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.

A. Power Module Design

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.

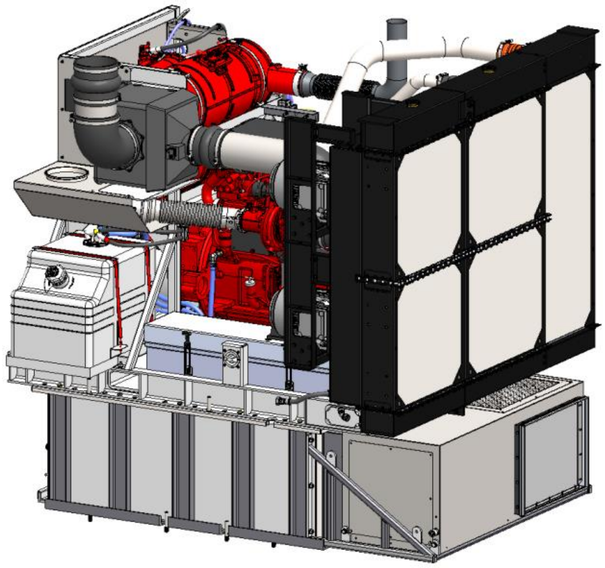

Fig. 9a. Left view of Power Module and cooling system.

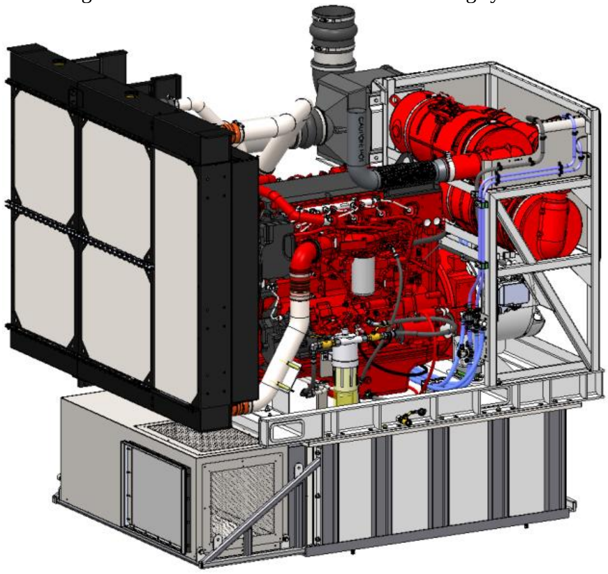

Fig. 9b. Right view of Power Module and cooling systems.

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. Fig.s 10a and 10b 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.

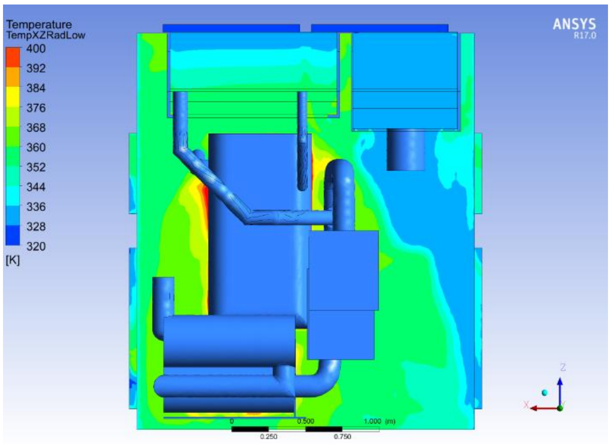

Fig. 10a. CFD results from engine compartment (top view).

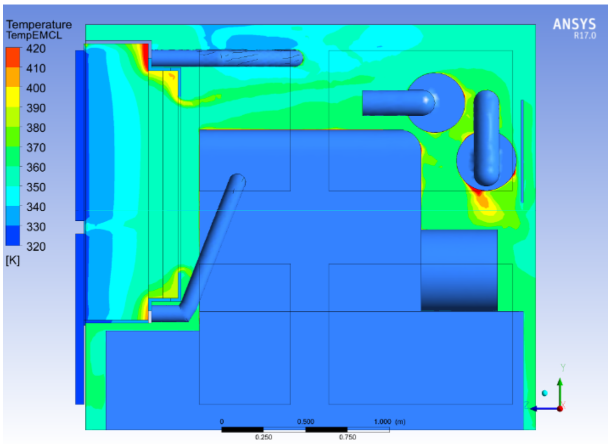

Fig. 10b. CFD results from engine compartment (side view).

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. Fig. 11 shows air velocities through the cooling passages. The flow is not perfectly uniform but is sufficient to prevent any localized hot spots.

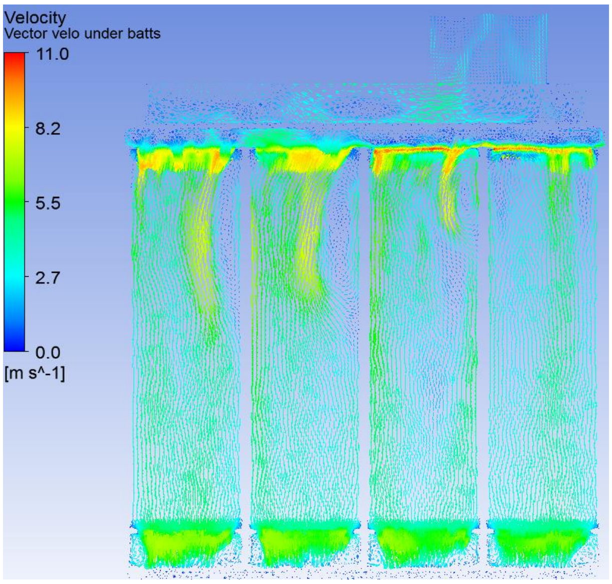

Fig. 11. CFD results from Energy Storage Module.

B. Electrical Packaging

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.

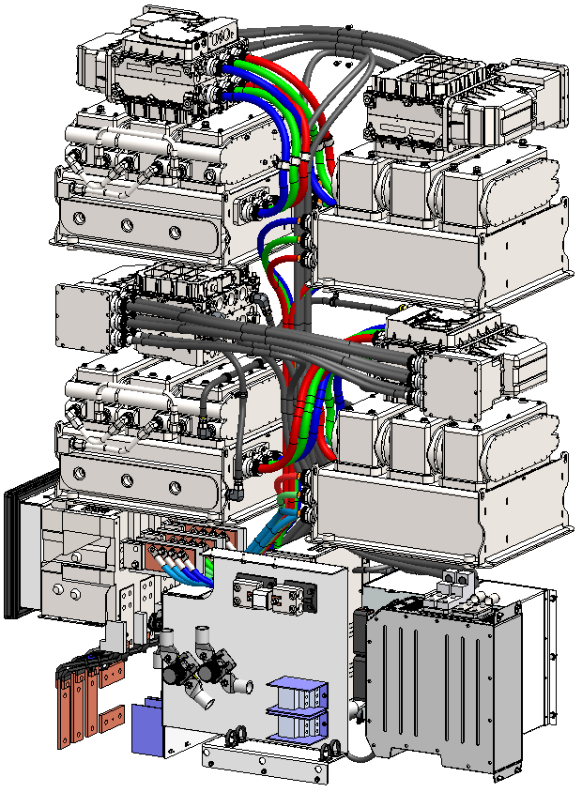

Fig. 12. Compact packaging of electrical equipment.

V. 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 Fig. 13.

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.

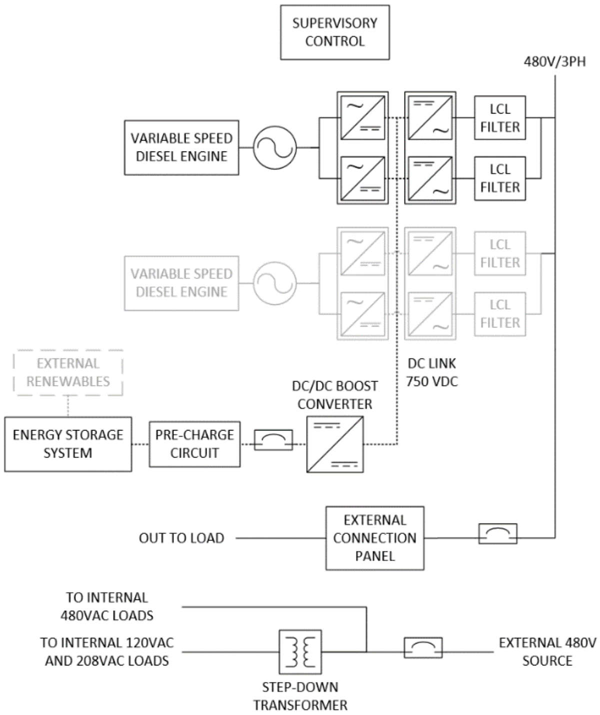

Fig. 13. Test system architecture.

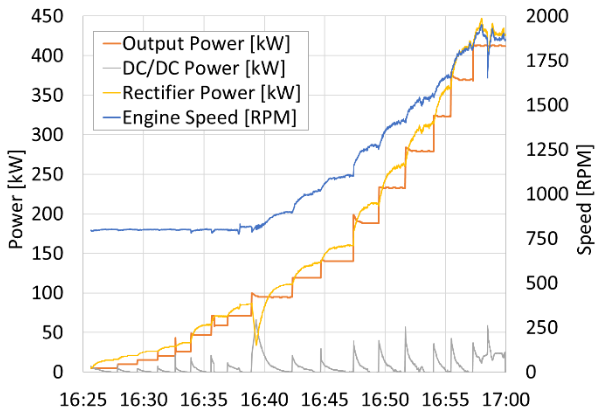

Fig. 14. Test results from power ramp up to full load.

Fuel consumption results from testing, shown in Fig. 15 (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 greater than 60% reduction in fuel consumption at 100 kW and greater than 40% reduction in fuel consumption at 200 kW 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.

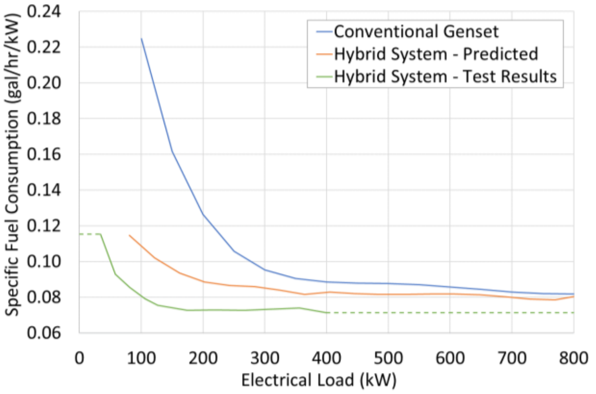

Fig. 15. Fuel consumption test results.

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.

VI. Conclusions

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

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

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