Reducing Fuel Consumption in a Forward Operating Base using an Energy Management System

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Abstract—This paper presents the benefits of transitioning from traditional generator employment in a Forward Operating Base (FOB) to an alternative architecture using a power electronics based Energy Management System (EMS). The EMS provides an interface between power sources, loads, and energy storage elements to form a microgrid. Using power electronics and programmable logic, the EMS enables more efficient generator utilization by matching real-time load demand to the smallest capable power source, reducing overall fuel consumption. The EMS offers redundancy as it can connect any one of multiple power sources to critical loads. A hardware-based laboratory experiment demonstrates the ability to transition from one power source to another while providing uninterrupted current to the load. The results of the experiment validate a Simulink model of the EMS. An example load profile was applied to the model to compare overall fuel consumption between the traditional architecture and the EMS-enabled microgrid.

I. INTRODUCTION

A Marine Corps Forward Operating Base (FOB) is a self-contained military base designed to support combat operations in an austere environment, often without pre-existing infrastructure. Similar in function to a permanent military base, a FOB contains planning spaces, billeting tents, and a variety of equipment which all require electricity. Lacking a utility grid, the primary source of a FOB’s electrical power is provided on-site by diesel generators.

Marines and soldiers are responsible for the transportation, safe employment, maintenance, and refueling of forward-deployed generators. These efforts enable sustained generator operation but also impose significant logistical challenges to deployed forces. For instance, the cost of fuel alone is a tremendous financial burden to the Department of Defense (DoD) at an estimated $400 per gallon delivered to a FOB [1]. In addition to the high dollar cost of fuel, the necessity of resupply convoys to deliver the fuel poses significant risk to U.S. armed forces. Former Commandant of the Marine Corps, General James Conway, related that 10–15 percent of Marine casualties occur during fuel and water convoy operations alone [2]. More efficient generator use presents an opportunity to reduce a FOB’s overall fuel consumption and, in turn, save money while reducing risk to American troops.

On a typical FOB, each generator is connected to its own set of loads and operates independently from other generators. Most of the time generators operate at low load. The fuel efficiency of a diesel generator is related to its electrical loading, as shown in Figure 1 for an example 10 kW tactical quiet generator (TQG). Generators operate most efficiently when they are fully loaded.

The objective of this research is to introduce an Energy Management System (EMS) into the FOB power system in order to more efficiently utilize generators and reduce overall fuel consumption. The EMS provides an interface between power sources, loads, and energy storage elements to form a microgrid. Using power electronics and programmable logic, the EMS provides capabilities such as power source selection, load control, power metering, power flow control, and peak power management [4].

For a given load a smaller generator at a high operating point is more efficient than a large generator at a low operating point in terms of fuel consumed per power delivered to the load (Figure 1). The EMS enables increased efficiency by ensuring that the smallest generator is selected to power the loads. The EMS provides an interface between
loads, power sources, and energy storage elements, as shown in Figure 2. If the batteries are charged and sufficiently rated, the EMS can shut down both generators and draw power from batteries alone.

![Figure 2](image1.png)

Figure 2. The EMS provides an interface between loads, power sources, and energy storage elements.

This paper is organized as follows. In section II a laboratory experiment is presented to demonstrate continuity of service to the load when a source is connected or disconnected. The experimental measurements are compared to the simulation results obtained by modeling the system in Matlab/Simulink. The validated model is used to simulate the scenarios presented in the following sections. Section III presents a traditional FOB power system scenario with two generators operating independently. The effect of using an EMS on the FOB power system is demonstrated in section IV where reduced fuel consumption is computed. Conclusions and future work are presented in section V.

II. LAB DEMONSTRATION AND SIMULATIONS

A laboratory experiment was conducted to demonstrate the EMS’s ability to disconnect from an external voltage source, operate using batteries alone and then reconnect to an external voltage source while maintaining uninterrupted current to the load. The electrical schematic for the hardware set up in the laboratory is depicted in Figure 3. The EMS box in Figure 3 includes the battery pack, buck/boost converter, and H-bridge converter which allow the EMS to inject current to power a load or draw current to charge the battery pack. A PCB mounted integrated power module using six IGBTs and antiparallel diodes was used to implement the H-bridge (2 legs) and the buck boost converters (third leg). Logic stored on a field programmable gate array (FPGA) dictates which power source the EMS selects based upon the load’s power demand.

If no generators are connected then the EMS is the sole power provider and operates as a voltage source, drawing power from the batteries. When a generator is connected the EMS can operate in one of the following modes:

- Charge the batteries, in which case the H-bridge works as a rectifier and the third leg operates as a buck converter.
- Supply additional current to the load, thus the H-bridge operates as an inverter controlled as a current source and the third leg boosts the voltage.
- Standby mode, monitoring the load demands.
- Peak power management by load shedding and/or generator connect/disconnect.

For the experiment presented in this paper $V_{sA}=V_{sB}=116$ Vrms, $L_{sA} = L_{sB} = 300 \ \mu H$, $L_{fil} = 1160 \ \mu H$, $C_{fil} = 12 \ \mu F$, and the load is a 109 $\Omega$ resistor. Six 12-V lead acid batteries are used, producing 72V dc output. The boost converter raises this voltage to 200V creating a DC bus for the H-bridge converter. A thyristor, Crydom CWD2410-10, is used as the disconnect/connect switch. The main power supply is used for both voltage sources, since they operate separately. The assumption is that a diesel generator’s output voltage does not differ much from the voltage available from the grid in the laboratory.

A photograph of the laboratory experiment is presented in Figure 4. The batteries are on the top left corner while the electronics, including three printed circuit boards (PCBs) are visible on the front. Two of the three PCBs are custom while the third one is a Xilinx FPGA development board [4].

The handoff from one voltage source to the other is demonstrated by the experimental set up shown in Figure 3 in two steps. In step 1 the EMS disconnects from $V_{sA}$ by turning off a thyristor. Once disconnected from $V_{sA}$, the EMS draws power from the batteries as it waits for $V_{fil}$ to synchronize with $V_{sB}$. Once synchronized the EMS connects to $V_{sB}$ at the next $V_{fil}$ zero crossing using a thyristor switch as shown by Step 2.

![Figure 3](image2.png)

The experimental voltages and currents produced when disconnecting the EMS from $V_{sA}$ are shown in Figure 5, and the corresponding waveforms for the connection to $V_{sB}$ are shown in Figure 6. In these figures $V_{fil}$ is the output bus voltage seen by the load, $I_{EMS}$ is the current injected from the H-bridge inverter, $I_{load}$ is the current through the load...
resistor, and $I_{sa}$ & $I_{sb}$ are the source currents from $V_{sa}$ and $V_{sb}$, respectively. The two sets of experimental plots demonstrate that the load does not experience any disturbance when a generator handoff occurs.

From Figure 5 it can be noted that just before $V_{sa}$ is turned off, there is a moment when current flows between the main power source and the EMS, thus producing a spike in the $I_{sa}$ and $I_{EMS}$ waveforms because the main power and the EMS are both trying to control the AC bus voltage. A small angle or phase difference between the EMS output voltage and the main power supply voltage cause a discontinuity to occur when $V_{sb}$ gets connected, as shown in Figure 6. These glitches do not affect the load, however they will be addressed in the future as the EMS digital controller gets further refined.

A physics based model of the circuit shown in Figure 3 was implemented using the Matlab/Simulink software. The voltage sources $V_{sa}$ and $V_{sb}$ were simulated using ideal voltage sources, while all other circuit parameters were set to match the laboratory set up.

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Additionally the thyristor switch controlled by the EMS to connect and disconnect the source contributes to the noise observed in the experimental waveforms.

III. TRADITIONAL GENERATOR EMPLOYMENT

A traditional method of generator employment is commonly used in FOBs where each generator is directly connected to its own set of loads [5]. An example of traditional two-generator employment is shown in the top pane of Figure 9. A notional profile representing each of the two generator’s load demand, as well as their sum, is depicted over a 24-hour period in the bottom pane of Figure 9. By visual inspection it is clear that both the 5 kW and 20 kW generators run at less than 50 percent of their rated maximum load throughout the notional scenario. Since a generator’s efficiency is directly proportional to its loading, such low generator loading as presented in Figure 9 gives room for optimization.

Fuel flows were estimated using each generator's capacity, operating point, and data from [6] and [7]. The fuel flow curves used for the generators in this paper are shown in Figure 10. Corresponding linear best-fit equations for these curves are given in Table I where the independent variable x represents the generator's operating point expressed as a percentage. Generator loading, fuel flow data, and fuel consumed by each generator under the traditional method of employment are summarized in Table II. Using the traditional method of generator employment for the load profile in Figure 9, the data in Table II shows that the two generators consumed a total of 22.7 gallons of fuel in a 24-hour period.

In the next section these results will be compared to the scenario where an EMS manages the loads and the generators, together with a battery pack, for the same load profile.

![Figure 9. Traditional two-generator handling of the loads.](image)

![Figure 10. Fuel flow curves for the generators used in this paper.](image)

### TABLE I. GENERATOR FUEL FLOW LINEAR BEST-FIT EQUATIONS.

<table>
<thead>
<tr>
<th>Generator Size</th>
<th>Fuel Flow (gph)</th>
<th>Fuel Consumed (gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 kW</td>
<td>( f(x) = 0.0046x + 0.113 )</td>
<td>6.024</td>
</tr>
<tr>
<td>15 kW</td>
<td>( f(x) = 0.0098x + 0.2419 )</td>
<td>2.0815</td>
</tr>
<tr>
<td>20 kW</td>
<td>( f(x) = 0.0169x + 0.4163 )</td>
<td>1.87335</td>
</tr>
</tbody>
</table>

### TABLE II. TOTAL GENERATOR FUEL CONSUMPTION USING TRADITIONAL GENERATOR EMPLOYMENT.

<table>
<thead>
<tr>
<th>Power Source</th>
<th>Time of Day (hrs)</th>
<th>Duration (hrs)</th>
<th>Generator Load (kW)</th>
<th>Generator Operating Point</th>
<th>Fuel Flow (gph)</th>
<th>Fuel Consumed (gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 kW Gen</td>
<td>0000-2359</td>
<td>24</td>
<td>1.5</td>
<td>30.00%</td>
<td>0.251</td>
<td>6.024</td>
</tr>
<tr>
<td>20 kW Gen</td>
<td>0000-0500</td>
<td>5</td>
<td>0</td>
<td>0.00%</td>
<td>0.4163</td>
<td>2.0815</td>
</tr>
<tr>
<td></td>
<td>0500-1000</td>
<td>5</td>
<td>4.6</td>
<td>23.00%</td>
<td>0.805</td>
<td>4.025</td>
</tr>
<tr>
<td></td>
<td>1000-1430</td>
<td>4.5</td>
<td>7.5</td>
<td>37.50%</td>
<td>1.05</td>
<td>4.725</td>
</tr>
<tr>
<td></td>
<td>1430-1930</td>
<td>5</td>
<td>4.6</td>
<td>23.00%</td>
<td>0.805</td>
<td>4.025</td>
</tr>
<tr>
<td></td>
<td>1930-2359</td>
<td>4.5</td>
<td>0</td>
<td>0.00%</td>
<td>0.4163</td>
<td>1.87335</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22.75385</td>
</tr>
</tbody>
</table>
EMS critical bus, and the non-critical loads are connected to the EMS non-critical bus, as shown in Figure 11.

Critical loads are those electrical devices that must be powered at all times to ensure safety or mission success. Non-critical loads may be briefly turned off without causing a major disruption to safety or operational requirements. In order to use the same load profile for both the traditional and EMS-enabled scenarios, the two sets of loads were separated into the same groups. The loads connected to the 5 kW and 20 kW generators in Figure 9 correspond to the critical and non-critical loads, respectively, in Figure 11.

Another difference of the EMS-enabled setup as compared to the traditional method of generator employment is that no more than one generator is used to power the loads at any given time. In other words, for the architecture shown in the top of Figure 11, the EMS may connect to Generator 1, Generator 2, or operate solely on battery power.

Design principles guiding EMS logic are as follow:

- Provide uninterrupted power to critical loads at all times
- Shed non-critical loads when necessary to maintain power to the critical loads
- Use the battery bank to supplement power to maintain generator operation no higher than 100%
- Utilize the battery bank or the smallest generator possible to supply power to the loads

Ideally, the EMS can draw power solely from the battery bank during periods of minimal load demand, thereby saving fuel because the generators are shut down. The EMS enabled topology explored in this section assumes a battery bank of 150 Genesis NP12-12 12 volt lead-acid batteries with a total useable capacity of 64.8 MJ. This capacity is based upon a maximum total battery power draw of 3 kW over a six hour time period. This capability creates the potential for the desired batteries-only mode of operation during extended periods of low loading.

Logic was implemented in a Simulink model to explore how the EMS handled the notional 24-hour load profile used in Figure 11. An overview of the logic flowchart is shown in Figure 12.

In Step 1 of the flowchart the EMS measures the average power demanded by the load. In step 2 the EMS compares the load demand to the capacity of the power source that is presently connected. The connected power source could be the 3 kW battery pack, the 5 kW generator, or the 15 kW generator. If a generator is connected then the EMS may also inject up to 3 kW of additional power from the battery pack in order to maintain generator loading no higher than 100 percent. If the battery pack decreases below a 20% state of charge (SoC) the EMS connects to the next largest generator to enable battery charging.

Step 3 takes corrective action in the event of a source power deficit or a generator power excess. Most
importantly, if the load demand exceeds the source capacity then the EMS sheds the non-critical bus to preserve uninterrupted power to the critical loads. Alternatively, if a generator is being used to power the loads and it has excess power then the EMS will use this excess power to recharge the batteries.

Assuming the EMS has completed any required actions from Step 3 it then executes a power-source handoff as shown in Step 4. When a handoff occurs, the EMS first sheds the non-critical bus (if not already shed in Step 2). This shed event is important because it reduces the potentially large load that would be placed upon the battery pack for the duration of the handoff when neither generator is connected. An exception to this is when the EMS transitions from a generator to the battery pack. If the EMS selects the battery pack as the desired power source it is implied that batteries are capable of handling the load and thus load shedding is not necessary.

When the handoff to the desired power source is completed, Step 5 dictates that the EMS will restore the non-critical bus. The EMS continues to sense the load demand from Step 1 and make power source handoff decisions as necessary.

The logic from Figure 12 was applied to the notional 24-hour load demand shown in Figure 11. Boxed regions surrounding different portions of the total load demand are annotated in Figure 11. Each region defines the period of time in which the EMS remained in a particular power source configuration. An associated numeric label corresponding to each region relates to information contained in Tables III through V. It was assumed that the battery bank was fully charged at the beginning of the simulation.

Data regarding which generator the EMS's logic chose to power the load, the loading placed upon the generator, the mode of battery operation (either off, supplying power to the load, or drawing power to re-charge), and the battery state of charge is summarized in Table III. More detailed battery SoC tracking is shown in Table IV, and the resulting total fuel consumption over the 24-hour period is calculated in Table V.

In the EMS-enabled scenario, the total fuel consumed by the gas generators was 11.2 gallons over the 24-hour period, approximately one-half of the daily fuel consumed by the traditional method of generator employment from Table II.

### TABLE IV. BATTERY BANK SOC CORRESPONDING TO REGIONS IDENTIFIED IN FIGURE 11.

<table>
<thead>
<tr>
<th>Region</th>
<th>Duration (hrs)</th>
<th>Battery Load (kW)</th>
<th>Initial Capacity (MJ)</th>
<th>Energy Drawn (MJ)</th>
<th>Remaining Capacity (MJ)</th>
<th>Initial SoC</th>
<th>Final SoC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.1</td>
<td>64.8</td>
<td>100.0%</td>
<td>37.8</td>
<td>62.2 100.0%</td>
<td>58.30%</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>1.1</td>
<td>37.8</td>
<td>19.8</td>
<td>18.0 100.0%</td>
<td>27.80%</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.17</td>
<td>-6</td>
<td>18</td>
<td>-46.8</td>
<td>64.8 100.0%</td>
<td>27.80%</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.33</td>
<td>0</td>
<td>64.8</td>
<td>0</td>
<td>64.8 100.0%</td>
<td>100.0%</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1.1</td>
<td>64.8</td>
<td>19.8</td>
<td>45.0 100.0%</td>
<td>69.40%</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.57</td>
<td>-3.5</td>
<td>45</td>
<td>-19.8</td>
<td>64.8 100.0%</td>
<td>69.40%</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2.92</td>
<td>1.5</td>
<td>64.8</td>
<td>15.8</td>
<td>49.0 100.0%</td>
<td>75.60%</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE V. GENERATOR SELECTION, LOADING, AND FUEL CONSUMPTION FOR TOTAL LOAD PROFILE IN FIGURE 11.

<table>
<thead>
<tr>
<th>Region</th>
<th>Selected Generator</th>
<th>Duration (hrs)</th>
<th>Generator Load (kW)</th>
<th>Generator Operating Point</th>
<th>Fuel Flow (gph)</th>
<th>Fuel Consumed (gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NONE</td>
<td>1</td>
<td>1.5</td>
<td>100%</td>
<td>0.573</td>
<td>2.865</td>
</tr>
<tr>
<td>2</td>
<td>5 kW</td>
<td>0.5</td>
<td>5</td>
<td>100%</td>
<td>0.573</td>
<td>2.865</td>
</tr>
<tr>
<td>3</td>
<td>15 kW</td>
<td>2.17</td>
<td>15</td>
<td>100%</td>
<td>1.23</td>
<td>2.6991</td>
</tr>
<tr>
<td>4</td>
<td>15 kW</td>
<td>2.33</td>
<td>9</td>
<td>60%</td>
<td>0.83</td>
<td>1.9339</td>
</tr>
<tr>
<td>5</td>
<td>5 kW</td>
<td>5</td>
<td>5</td>
<td>100%</td>
<td>0.573</td>
<td>2.865</td>
</tr>
<tr>
<td>6</td>
<td>5 kW</td>
<td>1.57</td>
<td>5</td>
<td>100%</td>
<td>0.573</td>
<td>0.89961</td>
</tr>
</tbody>
</table>

TOTAL: 11.2326

This paper included various presumptions in order to overcome information gaps. These ranged from the load profile used in the notional 24-hour scenario to the generators’ fuel flow rates with respect to loading. In addition, the computer modeling assumed certain ideal factors such as lossless power electronics and perfectly sinusoidal voltage sources, which do not exist in real life. However, the purpose of this paper is to explore the concept of employing generators in a more efficient manner. To this end the two scenarios are compared fairly using the same assumptions for both scenarios where a decision had to be made.

### V. CONCLUSIONS AND FUTURE WORK

The integration of the EMS into a FOB power system decreases overall generator fuel consumption while still providing necessary power to the loads. The decreased fuel consumption results from optimization in a variety of areas. First, the EMS uses the battery pack to provide power in times of low loading, meaning the generators are shut off and not consuming any fuel. Second, the battery pack’s supplemental power allows a 15 kW generator to be substituted for the 20 kW generator in the traditional
scenario. This is beneficial because the 15 kW generator has a lower fuel flow than the 20 kW generator for a given load.

Third, the EMS only operates one generator at a time. The chosen generator is the smallest option available that can power the loads while the other generator is shut down. The data in Table V show that the generators operate at 100% load most of the time. In general the generators’ operating points are consistently higher than those shown in Table II for the traditional method of generator employment.

The 24-hour load profile used in this thesis might seem unrealistic; that is, a set of loads with a 20 kW peak requirement never exceeded 9 kW in the notional power profile. Surprisingly, though, such under-utilization is quite common [8]. Data collected in the field shows that FOBs contain as much as 115 kW of generator capacity for total load profiles that, in reality, seldom reach above 45 kW [5]. The EMS serves a purpose in larger microgrid architectures above 20 kW as well. Excessive generation capacity drives traditional military generator employment, but in reality these generators never operate in the most efficient manner because doctrine limits them to 80 percent loading at best. As demonstrated in this paper, the EMS enables generators to run up to 100 percent with the battery pack ensuring additional power is available when needed.

Future investigations into the role of alternative and renewable energy sources in the EMS architecture will prove enlightening as well. The EMS may incorporate solar or wind power to charge the battery pack, alleviating some of that requirement from the generators.

REFERENCES


