Optimizing Off-Grid Hybrid Generation Systems[1]

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Introduction

The United States Coast Guard operates more than 20 remote radio repeater sites known as the National Distress System (NDS). The sites are located on remote mountain tops along the Alaska coast line. The Duke Island site is shown in Fig 1. These sites must be operational 24 hours per day, 7 days a week, 365 days a year in support of the maritime activities along the Alaska coast. The purpose of these sites is to relay emergency radio distress calls made by ships at sea requesting Coast Guard assistance.

Figure 1 Duke Island NDS

Electric power at each site is supplied by propane generators, photovoltaic arrays, and valve regulated lead-acid batteries. Because of their remote locations, freighting propane fuel and replacement batteries by helicopter to these remote mountain tops is a costly proposition for the Coast Guard. For the past year Sandia National Laboratories (SNL) has conducted a test program, co-funded by the Coast Guard and the DOE Energy Storage Systems Program, in an attempt to optimize the remote systems operational strategy to minimize fuel consumption and maximize battery life.

A test strategy was developed to compare two identical NDS power systems at the SNL Distributed Energy Test Laboratory; the first, referred to as the ACONF System, operating under the control of the Sandia-patented ACONF advanced hybrid system controller; the second, referred to as the Reference System, operating under the Mechron© controller currently in use at all remote NDS sites. The testing strategy put the two systems through their paces in much the same seasonal environment as that experienced at a selected NDS site. Testing was scheduled in such a way as to run each of the systems in a winter, spring/fall, and summer season to get a comparison of the operations based on the availability of the photovoltaic resource typical of the selected site. Preliminary modeling efforts indicated that a savings of up to 15% could be realized by the ACONF System. The test program was designed to confirm the prediction of the model. The photographs in figures 2 and 3 show the basic battery systems and the ACONF controller.

Figure 2 Reference and ACONF Batteries

Figure 3 ACONF Controller

1 Funded by the U.S. Coast Guard and the Energy Storage Systems Program of the U.S. Department Of Energy (DOE/ESS) through Sandia National Laboratories (SNL).

2 Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Both systems are configured to represent a mountaintop solar hybrid power system as currently implemented by the USCG. With the exception of the ACONF controller, both systems consist of the following components:

- A two-string, 24V battery, with 12 GNB 1000Ah VRLA cells in each string
- A Mechron© 7kW generator, with a 160amp, 30VDC battery charger/controller
- A DC power supply and appropriate software to simulate a 2.88-kW solar photovoltaic (PV) array
- A bank of power resistors to represent the load at a typical USCG site. At the nominal battery voltage, these resistors draw a load current of about 20amps.

Electrically, both systems are identical as shown in Figures 4 and 5, with one exception, the ACONF controller is inserted into the system between the battery and the DC bus. In the reference system, which emulates the current Coast Guard field operational strategy, all battery charging is provided by the generator or the PV. Typically the batteries are bulk charged to 90-95% state of charge and the generator is turned off. This operational strategy results in a chronically undercharged condition of the reference system battery, but it does result in operating the system at a higher efficiency as the generator is operated in a taper charging mode for a shorter period of time. In the ACONF control strategy, the generator is turned off immediately at the point the battery reaches regulation voltage and the battery charge controller is ready to initiate a taper charge. At that point, under control of the ACONF, String A is connected to the load and also provides finish charging to String B through a DC/DC booster which increases the String A voltage to the charge regulation voltage and maintains the voltage until String B is fully charged. At that point, both strings are connected to the load and discharge continues normally. During the next charge cycle, the rolls of String A and String B are reversed and String B supplies the load and finish charges String A. It is important to note that under the ACONF control strategy, the generator is run at its highest efficiency during all charging operations and the battery strings are alternately finish charged to maintain an optimum battery state-of-health.

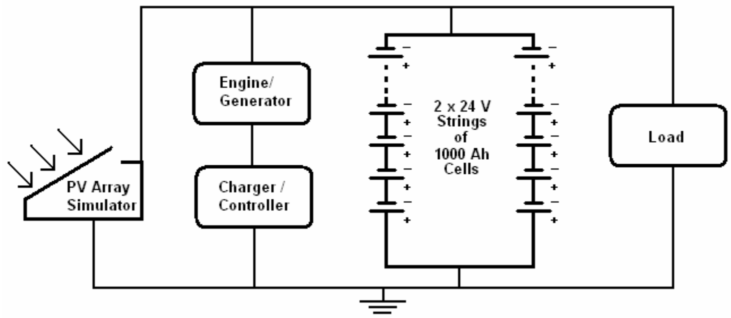

Figure 4 Reference System

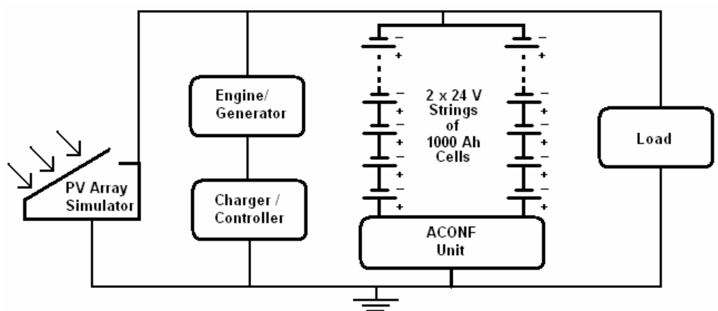

Figure 5 ACONF System

Results of Generator Operations for First Period of Testing

Summaries of the results of the cycle testing are shown in Table 1 for the REF system and in Table 2 for the ACONF system. It can be seen from Table 1 for the REF system that a total of 13 charges were completed and one was partially completed during the first period before the generator failed. Thus, 14 discharges were completed after the test sequence was started with a discharge.

Table 1 REF System First Period Data Summary

First Period ACONF Cycle Data				
ACONF	**Fuel Consumed (Gallons)**	**Cumulative Gallons Consumed**	**Generator Run Time (minutes)**	**Cumulative Generator Run Time (minutes)**
Winter Cycle	6.06	6.06	423	423
	9.7	15.76	503	926
	8.13	23.89	426	1352
	8.93	32.82	473	1825
	6.73	39.55	362	2187
	8.14	47.69	417	2604
	7.67	55.36	380	2984
	7.56	62.92	392	3376
	8.8	71.72	456	3832
	8.19	79.91	421	4253
	8.23	88.14	428	4681
	7.61	95.75	405	5086
	8.45	104.2	433	5519
	8.42	112.62	435	5954
	9.19	121.81	475	6429
	9.28	131.09	480	6909
	8.35	139.44	423	7332
Spring Cycle	8.86	148.3	456	7788
	8.47	156.77	434	8222

Table 2 ACONF System First Period Data Summary

For the ACONF system during the first period of testing, see Table 4, a total of 19 discharges and charges were completed before the testing was suspended because of the failure of the REF system generator.

Thus, the generator started somewhat more frequently for the ACONF system as compared to the REF system. However, it should be noted that one of the more subtle features of the ACONF technology, a solar optimization function that automatically schedules generator start times in coordination with sunrise and sunset, was not turned on during the First Period of testing. In order to test the efficiency of the solar optimization function to reduce generator start times, and also to evaluate the possible fuel saving that could result, the solar optimization function was implemented during the Second Period of testing.

In contrast to the frequency of generator starts, Tables 4 and 5 show that the generator run-time for the ACONF system is significantly less for the ACONF system than for the REF system. What this indicates is that, for the ACONF system, generator life should be extended somewhat and that generator maintenance requirements should be somewhat lower as compared to the REF system.

The advantage of the ACONF technology becomes even clearer when the fuel consumption measurements made during the first part of the Coast Guard testing are analyzed. This advantage is not apparent directly from the fuel consumption data in Tables 1 and 2, but can be clearly seen when these data are normalized to the energy delivered to the load for the two systems, as shown in Figure 6. The reason for adopting this metric to compare the fuel consumption for the two systems lies in the fact that there were several interruptions in the continuous cycling process because of minor component malfunctions for both systems.

To construct Figure 6, the energy delivered to the load was computed by summing the integrands of the product of the voltage and the current for each string from the beginning of the test to the point at which each charge with a generator was completed. Note that the fuel consumption for the last charge on the REF system is omitted since this charge was not completed due to generator failure.

Once the fuel consumption data is normalized as shown in Figure 6, it becomes quite clear that the fuel consumption by the ACONF system is significantly less than that for the REF system. From the data used to construct Figure 6 it can be calculated that the specific fuel consumption for the REF system was 0.28 gallons of propane consumed per kWh of energy delivered to the load over the entire first period, whereas the corresponding value for the ACONF system was 0.22 gallon/kWh. Thus the fuel consumption with the ACONF battery management controller was approximately 20% less than for the REF system.

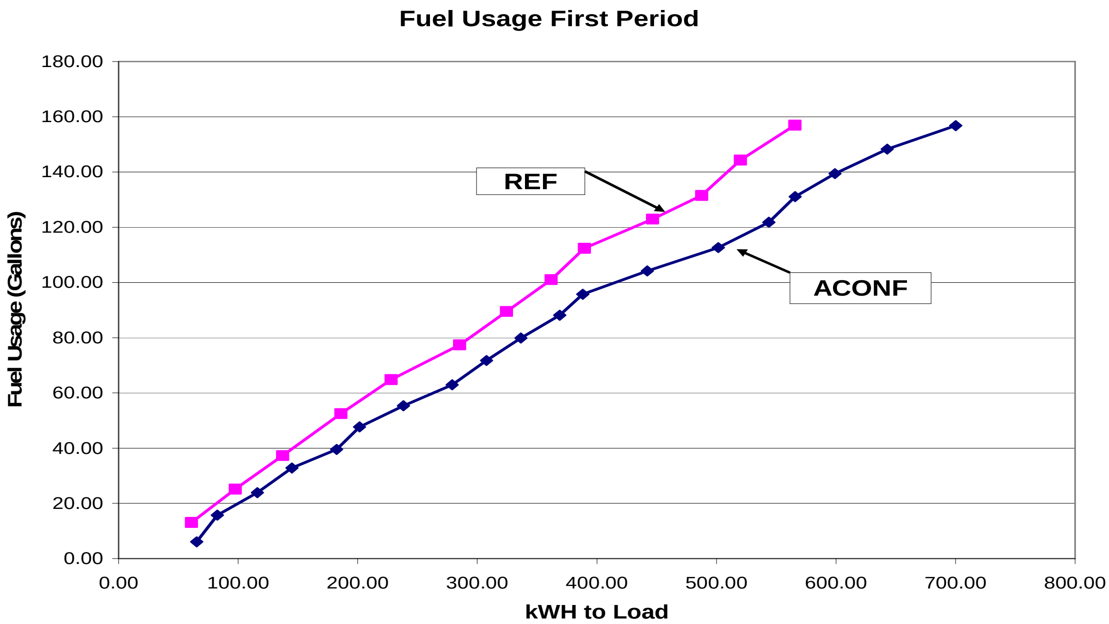

Figure 6 First Period Fuel Usage

Results of Generator Operations for Second Period of Testing

Table 3 shows a summary of the results of the cycle testing of the REF system during the Second Period of testing, i.e., for mid and late spring and for four weeks on each side of Midsummer. Analogous results for the ACONF system are shown in Table 4.

Table 3 REF System Second Period Data Summary

Second Period Reference Cycle Data					
REF	**Fuel Consumed (Gallons)**	**Cumulative Gallons Consumed**	**Generator Run Time (minutes)**	**Cumulative Generator Run Time (minutes)**
Spring Cycle	15.85	15.85	887	887
	17.36	33.21	962	1849
	14.37	47.58	820	2669
	12.47	60.06	648	3317
	12.15	72.21	742	4059
Summer Cycle	12.20	84.41	689	4748
	12.07	96.48	718	5466
	11.49	107.97	664	6130
	11.26	119.23	655	6785

Table 4 ACONF System Second Data Summary

Second Period ACONF Cycle Data					
ACONF		Fuel Consumed (Gallons)	Cumulative Gallons Consumed	Generator Run Time (minutes)	Cumulative Generator Run Time (minutes)
Spring Cycle		15.28	15.28	765	765
		10.05	25.33	471	1236
		9.91	35.25	486	1722
		8.99	44.23	436	2158
		8.34	52.57	607	2765
		7.06	59.63	351	3116
Summer Cycle		7.16	66.80	354	3470
		7.66	74.45	562	4032
		6.63	81.08	333	4365

From Tables 3 and 4, it can be seen that the same number of charges (9) were completed for both the REF system and for the ACONF system during the Second Period of testing. However, looking at the tables in more detail shows 5 charges during the spring season for the REF system versus 6 for the ACONF system. Also there were 4 charges for the REF system and 3 for the ACONF system during the summer season. From these results in comparison to those for the Winter and early-Spring periods cited above, it is clear that implementation of the solar optimization function did indeed reduce the number of generator starts for the ACONF system, as expected. In addition, the cumulative generator run time for the ACONF system was less than 2/3 that for the REF system, offering further to the expectation that generator maintenance should be less costly for an NDS site with an ACONF system than with the current implementation.

In a similar fashion to the First Period of testing, we show in Figure 7 a plot of the propane consumed by the generator as a function of the kWh of electrical energy delivered to the load.

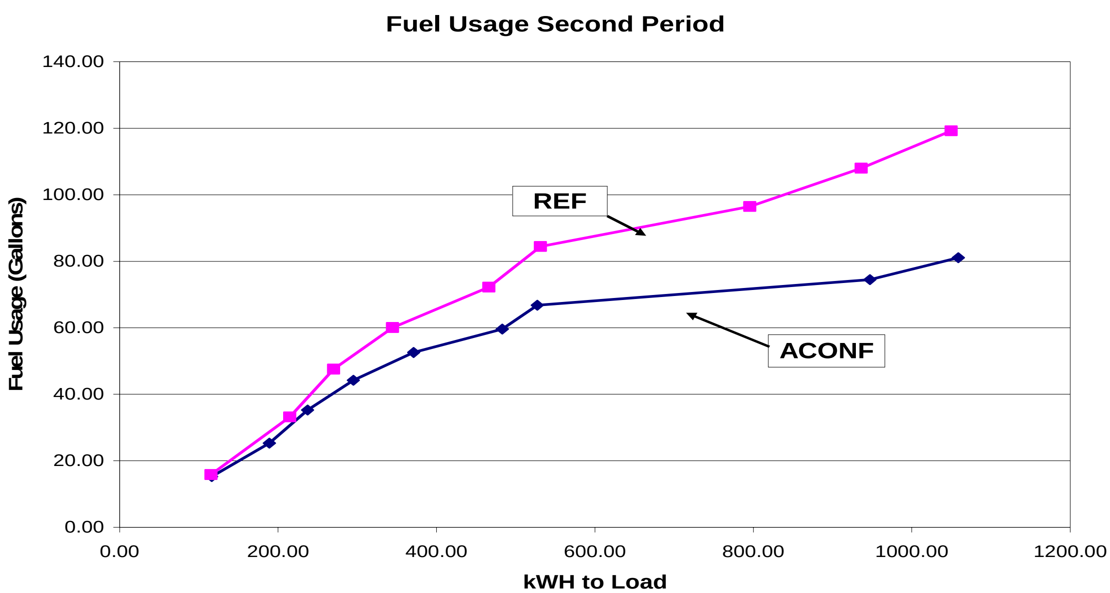

Figure 7 Second Period Fuel Usage

From examination of Figure 7, it is once again apparent that there are significant savings in fuel when using the ACONF in comparison with the REF system. Indeed, at the end of the test, it can be calculated that the ACONF system required 32% less fuel to operate than the REF system for the same amount of energy (kWh) delivered to the load.

Some part of the increased fuel savings in the Second Period compared to the First Period (32% versus 20%) can be attributed to the differing seasons (late Spring and Summer rather than Winter and early Spring) but some part of the increased savings are thought to be due to the implementation of the solar optimization function in the ACONF for the Second Period of testing. The relative importance of these factors can be determined only by further testing.

The slope of the lines in Figure 7 is the specific fuel consumption, i.e., the number of gallons of fuel consumed per kWh of energy delivered to the load. Close examination of Figure 7 indicates a change in the slope of the lines part way through the cycling, this corresponding to increased energy input from the (emulated) PV arrays.

Conclusions

Test results were somewhat surprising. During the winter and early spring cycling, the propane generator for the ACONF System consumed approximately 20% less fuel than that consumed by the Reference System. In contrast, during the late spring and summer cycling, fuel savings for the ACONF System soared to over 30%. In addition to the more efficient operation of the propane generator in the ACONF system during the summer test program, a PV optimization feature was implemented in the ACONF Controller that does not allow the spillage of PV energy. Overall test results for the ACONF system showed a fuel saving of approximately 25% for the entire test program. That is 25% less fuel consumed by the ACONF System delivering the same amount of energy to the load as the Reference System.

Results on what the impact is on battery state-of-health are still unknown as there has been no measured degradation in capacity in either of the systems. However, because of the alternate string finish charging of the ACONF battery, full capacity is predicted to be maintained much longer than that for the reference system. Testing continues by cycling both systems in the winter environment to see if an impact on capacity becomes noticeable for the current year of testing.

An ACONF system has been installed and is being tested at Duke Island for the period of one year. Data from that test activity will be available by mid-winter. At that time, program direction will be re-evaluated by the USCG in collaboration with the DOE/SNL Energy Storage Systems Program to determine what the next steps toward full implementation will be taken.