ACEP Report

GRIDFORM INVERTER TESTS AND ASSESSMENT

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Executive Summary

An inverter-battery system manufactured by Sustainable Automation Inc. (Sec. 3) underwent testing at the Alaska Center for Energy and Power's Power Systems Integration Laboratory (Sec. 2). The aim of the tests was to demonstrate that inverter-battery systems are a viable strategy for diesel-off mode operation of wind-diesel grids, and to investigate whether this particular inverter-battery system is ready to be deployed in rural Alaska.

The system tests showed that diesel-off mode is attainable with the grid-forming inverter tested here (GRIDFORM inverter by Sustainable Automation Inc.). The GRIDFORM inverter provided high quality power and grid stability in diesel-off operation. However, the tests and the design review also revealed several shortcomings of the equipment. It is recommended that these shortcomings be addressed before the GRIDFORM inverter-battery system is deployed to rural Alaska. In addition, the need for extensive operator training with these new technologies is significant and should be factored into a purchase decision.

Acknowledgement of Funding

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Project Overview

At a glance:

- Diesel-off mode in wind-diesel systems requires additional technology beyond what is required to integrate wind into a diesel grid.
- Sustainable Automation Inc. provided an inverter-battery system (grid-forming inverter) designed to operate an isolated grid in diesel-off mode.
- The grid-forming inverter system was integrated into a laboratory wind-diesel power grid and its performance to provide stable power in diesel-off mode was evaluated.

Utilities in rural Alaska typically produce electricity using diesel generators in isolated micro-grids. Since the 1980s several utilities have integrated wind power generators into their grids to supplement power production and mitigate high fuel costs. Wind power integration below 50% instantaneous power contribution is well understood. In this case the diesel gensets remain the prime power producer in the grid, and fulfill the function of keeping the grid stable by conditioning the power generated from wind turbines. More recent efforts are aimed at increasing the contribution of wind power to levels up to 100% thereby enabling to operate without diesel gensets being online. However, due to the typical nature of wind generators and the variability of the resource, this approach requires strategies to stabilize power quality and to manage drops of wind power production below load levels.

One strategy to achieve diesel-off mode is to include energy storage systems (ESS) into the grid. An ESS needs to be sized such that it can supply enough power to mitigate temporary reductions in wind power, at least long enough to bring a diesel genset back online. At the same time, an ESS should be capable of improving power quality by stabilizing frequency and voltage in the grid, and by providing sufficient reactive power support for the wind generators and loads.

The ESS tested in this case consists of an inverter-battery system. The function of the inverter is to convert power between alternating current (AC) on the grid side and direct current (DC) on the battery side. Furthermore, the inverter is capable of stabilizing the grid frequency and voltage, and can provide reactive power support. The system can operate standalone as an inverter-battery system with wind generators, or in conjunction with a diesel genset.

ACEP tested the grid-forming ability of a newly developed inverter-battery system, called GRIDFORM inverter by the manufacturer (Sustainable Automation Inc.). In order to determine whether the GRIDFORM inverter was capable of supporting an isolated micro-grid in diesel-off mode, it was integrated into ACEP's Power Systems Integration Laboratory (see Chap. 2) and subjected to test scenarios. In addition, the engineering of the GRIDFORM inverter was reviewed with respect to its utility to be deployed in rural Alaska.

'Grid-forming' is described in the literature as the capability of an inverter to operate in frequency and voltage control mode as an islanded grid. Distinctions are made between 'grid-forming' and 'grid-following', where grid-following is described as an inverter operating under real and reactive power set-points. Some authors define a third category (grid-supporting), best suited for micro-grids, meaning an inverter in voltage and frequency mode, that is sharing real and reactive loads via frequency and voltage control [1–9].

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2

ACEP Power Systems Integration Laboratory

At a glance:

- ACEP operates an isolated micro-grid laboratory at a similar scale as rural Alaskan power systems.
- The grid consists of a 320 kWe diesel genset, a 100 kW wind turbine simulator, and a 250 kW load bank.
- The system is setup for 480 VAC operation.

ACEP has developed a Power Systems Integration Laboratory to emulate typical rural Alaskan wind-diesel systems up to power levels of 500 kW. The purpose of the lab is to test technologies meant to increase power plant efficiency, as measured by the amount of diesel consumed per unit of energy produced, in a controlled setting which is readily accessible by road. Through this, the risk of acquiring sub-optimal equipment for rural Alaskan utilities is to be reduced by demonstrating and testing equipment designed/destined for rural Alaska before it is deployed.

The testbed setup utilized for the test of a particular piece of equipment can be adjusted depending on the equipment's typical and rated power levels, or based on the power levels of a given rural power plant.

For the test regiment described here the testbed was configured with a 320 kWe Caterpillar diesel genset, a 100 kW wind turbine simulator and a 250 kW/187.5 kvar variable load bank. The nominal grid voltage is 480 VAC, three-phase.

The wind turbine simulator, also a product of Sustainable Automation Inc., consists of two mechanically coupled induction machines, a motor and a generator. The motor is controlled by a variable frequency drive (VFD) and its output torque can be controlled via torque, power, or wind speed and wind turbine power curve time series, or set point inputs. The generator connects directly to the main grid bus. The power output is not conditioned.

The 250 kW/187.5 kvar variable load bank is a product of Load Technology, Inc. Load can be controlled in 5 kW and 3.5 kvar steps, independently of each other. The nominal voltage of the load bank is three phase 208 VAC, and it is connected to the grid through a Delta-Wye-connected transformer (Delta on 480 VAC, Wye on 208 VAC, 300 kVA). The lab setup for this test is shown in Fig. 2.1.

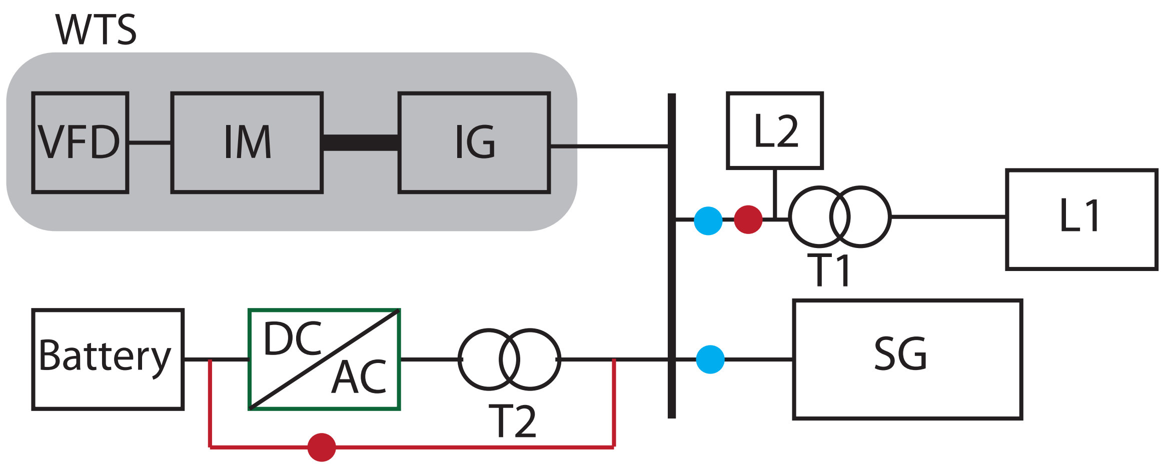

Figure 2.1: Single line drawing of Power Systems Integration Laboratory setup for the GRIDFORM inverter test. The GRIDFORM inverter is shown in green, connected to the battery and the isolation transformer (T2). The components of the wind turbine simulator (WTS) are shown on gray background. The induction motor (IM) drives the induction generator (IG) based on control signals transmitted to the variable frequency drive (VFD). Only the IG of the WTS is electrically connected to the grid, the VFD and IM receive external grid power. The main load bank (L1) is connected to the hybrid grid through a voltage transformer (T1). The load bank (L2) was used to simulate slight phase imbalances. The load bank connection and the connection to the synchronous generator (SG, diesel genset) were instrumented with WattsOn meters (blue dots). A Fluke 435 II Power Quality and Energy Analyzer (red dot) was connected to the load bank transformer for most tests. The exception is the inverter efficiency test, where the Fluke 435 II was connected to the grid side of the isolation transformer and the DC link of the GRIDFORM inverter (see Section 3.4.4).

3

GRIDFORM Inverter

At a glance:

- GRIDFORM Inverter is IGBT-based, rated at 200 kVA/160 kW.
- As per manufacturer, additionally, a synchronous condenser is required for full functionality.

The inverter-battery setup tested is a product of Sustainable Automation Inc., Boulder, CO[1] (SAI). The GRIDFORM inverter is a new product developed by SAI, with an American Superconductor PM3000 IGBT-based inverter module at its core. The inverter tested is accompanied by an Absolyte® GP valve regulated lead-acid battery bank, sized by SAI. The grid connection is made through a Delta-Wye isolation transformer (Wye on grid-side, Delta on inverter-side). The GRIDFORM inverter supplied for the lab is serial number 2, with serial number 1 being deployed at Kokhanok, AK, and a smaller development unit exiting at SAI facilities.

The specifications given by SAI for the GRIDFORM inverter are shown in Table 3.1.

The GRIDFORM inverter cannot support a grid without an inertial machine (genset, wind turbine, synchronous condenser, or similar) being online. The manufacturer suggests a combination of GRIDFORM inverter and a synchronous condenser if diesel-off mode is desired. In this case, the synchronous condenser can provide reactive power support, and be the back-up inertial machine, should the wind turbine(s) suddenly drop offline. This requirement is not an concern in the laboratory setting where

[1]Sustainable Automation Inc. ceased operation in December 2011. Final commissioning was performed by Sustainable Power Systems LLC. Sustainable Power Systems LLC does no longer offer Sustainable Automation Inc.'s line of products, but pursues different approaches to remote micro grid operation.

Table 3.1: GRIDFORM inverter specifications as per 'Energy Storage Inverter User Manual', Rev. 1, June 2012, provided by SAI.

Electrical Characterisitics

Rated AC power	200 kVA
Rated AC current	240 A
AC line-to-line voltage	480 VAC
Nominal battery voltage	336 VDC
Rated DC current	500 A
Nominal DC link voltage	750 VDC
Switching frequency	3 kHz

Environmental Characteristics

Storage temperature	-40 °C to 85 °C
Ambient operating temperature	-25 °C to 40 °C
Humidity	0 to 95% non-condensing
Altitude	<1000 m without derating

permanent grid stability is not an issue; a synchronous condenser was not part of the test setup. By some definitions (see Sec. 1), this renders the GRIDFROM inverter a *grid-supporting* inverter, as the synchronous condenser can be considered a source of reactive power on the grid with which the GRIDFORM inverter shares load via voltage control.

3.1 Inverter Design Review

At a glance:

- **Electrocution Hazard:** Placement of DC meter/relay is extremely dangerous.
- Placement of cable entry points vs connection points can be improved.
- Routing of internal connections and plumbing can be improved.

In the course of using the GRIDFORM inverter several design issues impacting installation and safe operation became apparent.

The cabinet in which the inverter was supplied is designed as a bottom entry for all electrical connections. The connection points within the cabinet do not lend themselves for this connection scheme, though. In a future iteration of the packaging, it is suggested to move all connection points to one location close to the design entry point for electrical connections. Similarly, the control system's customer connections are placed on the center door of the three door cabinet. Again it is suggested to move these connections to a more convenient location within the cabinet. It is also suggested to group all AC control breakers and DC control breakers in two easily accessible panels.

Several internal power connections are routed directly across metal bars and sharp edges, and are held in place with 1/8th inch zip ties and self-adhesive cable holders. After transport and low-duty operation, some of the connectors have already failed and, in some places, the cables show wear to their insulation.

The inverter can be controlled through a touchscreen interface at the center door. This interface allows the review of fault messages and resetting of faults. The only exceptions to this are DC bus over/under-voltage faults, which are generated through a meter/relay in the back of the cabinet. To clear these faults, the user has to reach over the DC bus link and capacitor bank (exposed bus bar; does not de-energize immediately upon opening breaker)[2]SAI. This creates an unnecessary electrocution hazard. Ideally, this fault could be reset at the front touch panel as is true for all other faults.

DC connector blocks and capacitor banks should be covered. This is especially true for the capacitor bank, which does not de-energize immediately upon DC breaker opening. In addition, AC filtering equipment should be contained; capacitors should have covers contain blow-outs that could destroy other equipment; resistors should have covers to protect technicians from potential burn hazards.

[2]The manufacturer notes that this relay can be set to non-latching in order to avoid this hazard. However, the unit was supplied as is and not modified by ACEP personnel, neither in software nor hardware, post commissioning.

Control power for the GRIDFORM inverter is supplied from the AC side of the inverter. Since this particular inverter cannot act as an uninterruptible power supply, this is not an issue here. However, should a future iteration of the product allow for standalone (no inertial machines) operation, control power should be provided from the energy storage side to allow for black-start capability.

The GRIDFORM inverter is liquid cooled, with a 50/50 glycol-water mix. The coolant has to be drained for transportation and long-term storage. Small amounts of coolant left in the cooling system can dry out in this case and form a flaky residue when new coolant is introduced into the cooling system. This residue caused a filter in the system to clog and subsequently a shut-down due to overheating. It is suggested that, when the cooling system is drained, it be flushed with clean water to avoid such issues.

3.2 Inverter Battery Interaction

The interaction between a bi-directional inverter and energy storage is not trivial. The GRIDFORM inverter employs a lead-acid battery bank to manage power import and export. It is the nature of lead-acid battery technology that maximum import/export power levels are a function of state of charge (SOC).

SAI has divided the charge levels of the battery into five quadrants - high-high, high, mid-range, low, and low-low. Grid-forming mode is not available in high-high and low-low state of charge; that is, the battery SOC needs to be kept between 79% and 24% for full operability of the system.

Optimal management of the battery system requires an additional level of control system. This control system would have to be adjusted to the particular battery system used, e.g., the system in Kokhanok, AK employs a different battery. SAI supplies a top-level control system, which was not available for the test performed here.

3.3 Data Acquisition Equipment Utilized

The testbed grid was monitored with several power meters during all tests. Two stationary WattsOn® 1100 meters by Elkor Technologies, Inc., were used to monitor voltage and current at the load bank transformer and the diesel genset to bus connection (Blue dots in Fig. 2.1). These meters allow power flow and frequency metering at 5s intervals.

A Fluke® 435 Series II Power Quality and Energy Analyzer was used to monitor power quality as seen at the load bank transformer (T1 in Fig. 2.1). This meter is capable of high frequency measurements. However, the recorded data is reduced to 1 sample/s and minima, maxima, amid averages are recorded for these intervals. The meter was placed at the load bank transformer as this location is the closest emulation of a station feeder. Additionally, a Fluke® 434 Series I Energy Analyzer was deployed to measured energy flow at the grid-side of the GRIDFORM inverter isolation transformer.

3.4 Grid-Forming Inverter Performance

At a glance:

- Power quality is good, with acceptable voltage dips under load changes.
- Diesel-off mode was demonstrated.
- Ride-through capabilities/fault hardiness could not be tested due to lack of equipment.
- Inverter efficiency is inversely proportional to loading and within 68 to 95%.
- Power level given in manufacturer's specifications could not be reached.

The focus of the testing described below is concerned with the diesel-off mode of the GRIDFORM inverter. In this mode, the GRIDFORM inverter provides support to variable generation sources, such as a wind turbine. It can sense whether additional power is needed to meet demand, or whether the variable power source is exceeding demand. Accordingly, the GRIDFORM inverter will provide power from/absorb power into the battery. In addition, the GRIDFORM inverter manages the power quality of the grid by adjusting voltages and frequency.

3.4.1 Power Quality

The power quality in the grid in diesel-off mode was monitored against ITIC/CBEMA power acceptability curves. The Fluke® 435 Series II Power Quality and Energy Analyzer at the load bank transformer (T1 in Fig. 2.1) was setup to record voltage dip and swell triggered-events slightly within the aforementioned acceptability curves. Only two voltage dip events were recorded in diesel-off mode: One during a sudden change in kvar loading, i.e., power factor change from 0.83 to 0.98 with demand and WTS both set to 50 kW; and one event during a series of rapid WTS output changes. During both events power quality remained within both the ITIC and CBEMA power acceptability curves, with voltage deviations no more than 150 V. Both events were shorter than 70 ms.

3.4.2 Diesel-off Mode

When the diesel genset is online, it usually regulates frequency and voltage in the grid. In this setting the GRIDFORM inverter can be used to provide kW/kvar support at given set-points . In diesel-off mode the GRIDFORM inverter provides voltage and frequency support to the grid.

The transition to diesel-off mode was demonstrated with the wind turbine simulator providing parts of the power demanded by the load bank (and inertia). The transition to diesel-off mode is quite smooth both in the voltage and frequency picture (Figs. 3.1 and 3.2).

Variable wind or variable loads do not have a significant effect on frequency stability. Only sudden load changes exceeding 100 kW resulted in frequency deviations larger than 0.03 Hz. Under the same conditions, voltages remained stable, with the exception of the dips discussed in Sec. 3.4.1.

The GRIDFORM inverter is designed to be operated within a Hybrid Supervisory Control System (HSCS) developed by SAI. This system would generally control transitions into and out of diesel-off mode, i.e., diesel synchronization and change of operating mode of the GRIDFORM inverter. This system requires that a Woodward EasyGen controller (or other automatically synchronizing tool) be in place on the diesel to control diesel-to-grid synchronization when bringing the diesel back online. This controller was not available at the time of testing. Nonetheless, manual synchronization to bring the diesel back online was successfully performed. Even with this crude method, no detrimental effect on power quality during the transition was observed.

3.4.3 Ride-through Capabilities

System robustness in fault and unusual load situations, such as phase imbalances, is a major concern for Alaskan utilities.

To test the GRIDFORM inverter performance under imbalanced load, a smaller resistive load bank was connected to the main load bank transformer. With this, phase to phase imbalances up to 19 kW could be simulated. The GRIDFORM inverter performed well under these conditions.

The lack of a fault simulator at the time of testing did not allow for investigation of the general fault-hardiness of the system. However, since the manufacturer recommends the parallel use of a synchronous condenser, at least a moderate level of fault hardiness of the GRIDFORM inverter-synchronous condenser combination can be expected.

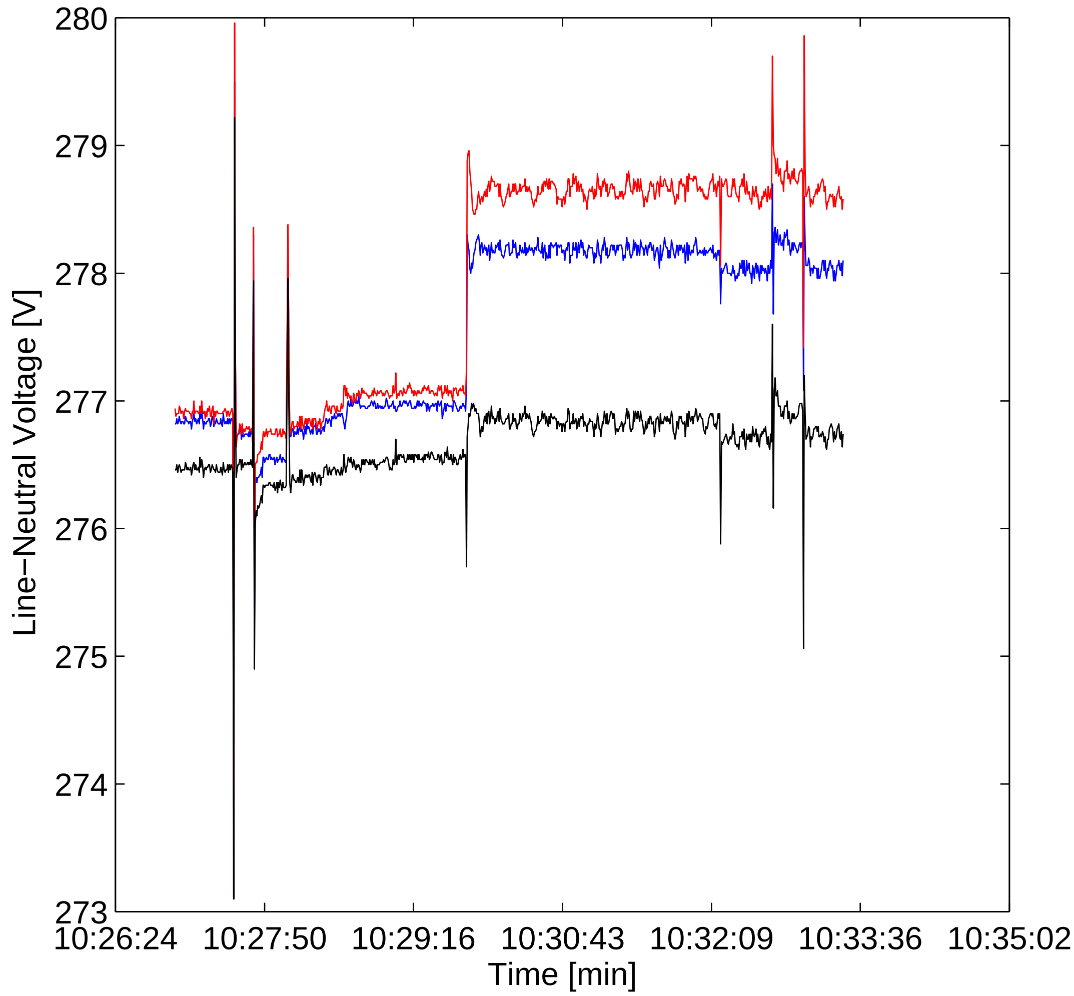

Figure 3.1: Voltage response during transition to diesel-off mode. Shown are average line to neutral rms voltages (blue - L1N, red - L2N, black - L3N). The transition occurs at 30 min. While the diesel provides a tighter spread of voltages on all lines, the GRIDFORM inverter voltage control keeps the line to neutral voltage on all three phases well within allowable bounds. The dips and swells in diesel-off mode are due to load changes. Data shown was taken with the Fluke® 435 Series II Power Quality and Energy Analyzer at the load bank transformer.

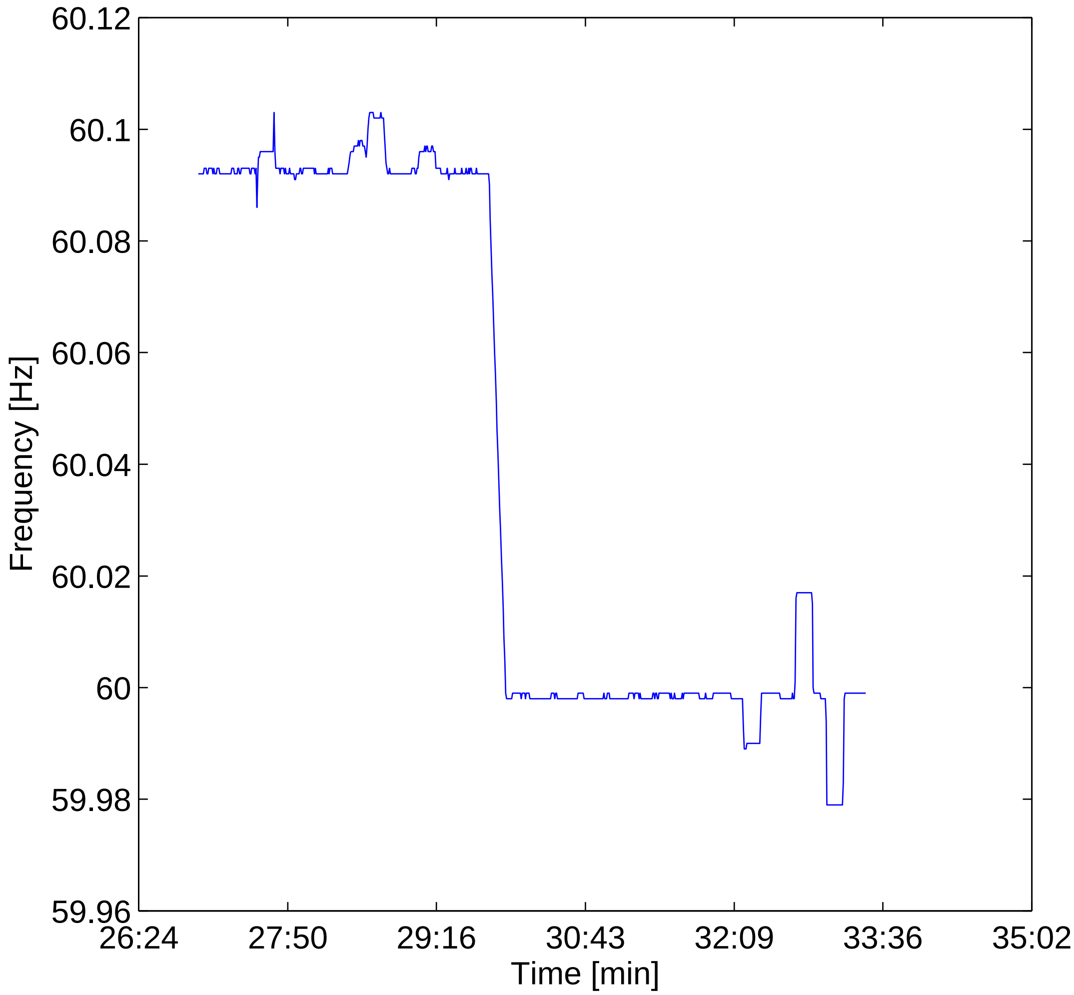

Figure 3.2: Frequency response during transition to diesel-off mode. The transition occurs at 30 min and the GRIDFORM inverter is able to hold frequency very close to the nominal 60 Hz. The deviations in diesel-off mode are due to load changes. Data shown was taken with the Fluke® 435 Series II Power Quality and Energy Analyzer at the load bank transformer.

3.4.4 Grid-Forming Inverter Energy Efficiency

The GRIDFORM inverter efficiency was assessed both for importing power to and exporting power from the battery. This assessment was performed with the GRIDFORM inverter in kW/kvar mode and the diesel being online. The reason for this was that power levels could exceed the maximum power output of the WTS. This did not occur due to other reasons (see Sec. 3.4.5). Efficiency was assessed using the Fluke® 435 Series II Power Quality and Energy Analyzer with the DC measurement performed at the battery to GRIDFORM inverter connection and the AC measurement taken on the grid-side of the isolation transformer[3] (Fig. 2.1, red line from the right of T2 to inverter-battery connection depicts the meter connections). The meter calculates energy efficiency internally. Due to the nature of the measurement, the given efficiency is only for the inverter, including the required isolation transformer. It does not include roundtrip efficiency of the battery.

The inverter system efficiency is logarithmically dependent on power levels (Fig. 3.3). At low power levels (< 30 kW), efficiencies between 68% and 88% are observed with the efficiency of charging the battery being slightly lower below 20 kW than the efficiency for discharging the battery. At about 20 kW this trend is reversed. At high power levels, importing power into the battery is between 90% and 95% efficient. While the efficiency of exporting power is about 5% lower for any given power level. The lower efficiency at low power levels does not necessarily pose a problem as total energy throughput at these levels will be low as well, that is, total energy loss will be low.

3.4.5 Limitations

During the efficiency test it was noticed that nominal power levels (160 kW, 200 kVA) could not be reached. The inverter went into a DC under/over-voltage fault at 106 kVA (discharging) and 87 kVA (charging) respectively. The test was performed between 63% and 60% SOC. Power levels where increased to the fault levels in 5 kW steps.

Block loading of the inverter led to over-/under-voltage faults at even lower power levels. It is suspected that the buffering (programming of PID controllers) for voltage control require more development[4].

[3]The transformer was included in the efficiency assessment as it is required for the grid-connection of the inverter.

[4]After consulting with the manufacturer about this problem, the battery was exercised (two full battery capacity tests and equalization cycles) in order to determine if this would improve performance. This had no effect on the maximum available power level, but more faults due to DC over-voltage, and DC over-current were encountered.

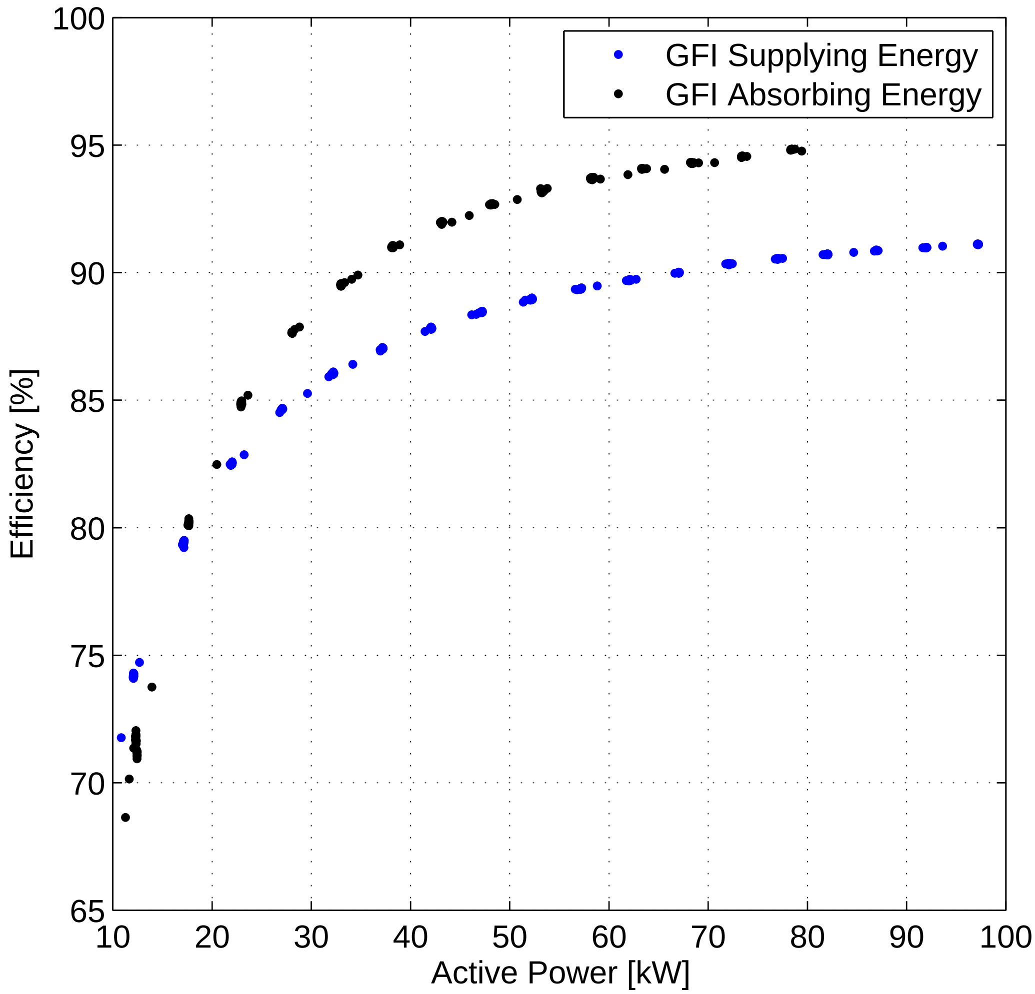

Figure 3.3: Efficiency vs active power. The GRIDFORM inverter exhibits up to 95% efficiency when absorbing power into the battery (black dots), and up to 91% efficiency when supplying power to the grid (blue dots). At low power levels efficiency is generally much reduced. Efficiency was assed using the inverter efficiency mode of the Fluke® 435 Series II Power Quality and Energy Analyzer with the DC measurement performed at the battery to GRIDFORM inverter connection and the AC measurement taken on the grid-side of the isolation transformer. The GRIDFORM inverter was in kW/kvar mode during this test with the kvar set-point constant at 35 kvar. The diesel was online.

4

Conclusion and Recommendations

At a glance:

- The operation of the grid-forming inverter as a means of operating in diesel-off mode has been demonstrated.
- Power quality and grid stability are within acceptable bounds.
- Further development is recommended before deployment to rural Alaska.
- Significant operator training is necessary for successful deployment of high-contribution renewable energy systems.

The GRIDFORM inverter-battery system supplied by SAI has been shown to be capable to act as energy storage solution that allows the operation in diesel-off mode in a wind-diesel grid.

The power quality and grid stability in diesel-off mode is managed by the GRIDFORM inverter and has been shown to be within acceptable bounds for smooth grid operation.

The inverter efficiency at low power levels is rather low. This would be further compounded by the roundtrip efficiency of the battery employed. While an economic and power flow study was not performed as part of this project, it is suspected that much of the operation of the GRIDFORM inverter would occur at fairly low power levels and, thus, the energy losses observed would have a significant impact during operation in a utility setting.

Power levels observed were well below the levels specified by the manufacturer. The reason for this is likely insufficient adjustment of the inverter controls to the battery dynamics. This, in combination with several design deficiencies (one of them dangerous) leads to the conclusion that the GRIDFORM inverter in its current form should not be deployed in rural Alaska. This is compounded by the fact that additional, costly equipment and controls are required to make full use of the diesel-off capabilities of the GRIDFORM inverter.

By no means is the above conclusion to be understood as a condemnation of the approach of using an inverter-battery system to achieve diesel-off operation in high contribution renewable energy situation. However, it is to be understood that the interactions between the inverter and the grid and the inverter and the energy storage system are by no means trivial. Thus, the design and control of such systems requires further development.

There are several suppliers of technology similar to the GRIDFORM inverter tested here. Some of these suppliers claim the capability to operate their inverter in diesel-off mode without the need of further equipment, e.g., a synchronous condenser. However, the total number of deployed systems is too small to conclude that any of them are fully proven and mature technology.

It is recommended that utilities, considering the deployment of a high-contribution renewable energy system with inverter-energy storage technology, require manufacturers to demonstrate their technology in full before a purchase is made. This would include, but is not limited to: 1) operation at advertised power levels both importing and exporting, 2) smooth transition from grid-following to grid-forming mode, 3) acceptable power quality in all operating modes, especially under block (un-)loading, 4) stable operation in grid-forming mode. Additional consideration has to be given to control systems. Most common SCADA systems will not be able to manage diesel-off mode without being adjusted.

Furthermore, utilities should be aware that their operating staff will require significant training to efficiently operate and service such technology, i.e., inverter and battery trouble shooting skills, network trouble shooting skills, knowledge of save operation of DC power systems are required, in addition to the common skills of operating a wind-diesel power system.

Appendix A

Independent Review by Philip Maker

Is inverter-based energy storage a viable option for high-contribution renewable energy systems? Yes: its been installed in a variety of sites but the number of sites running at high contribution remains small. ABB and SMA are two larger companies that can provide systems at a variety of sizes in this area that have been demonstrated to work in the long term. The critical issues are:

- Fault behavior particularly as compared to a diesel generator.
- Integration into a complete control system.

What are the general technological road blocks to implementing successful inverter-based high-contribution systems (ESS, and inverter control)?

- System and device integration.
- Front inverter design and control.
- Reliability and system longevity.

Is this particular inverter (plus synchronous condenser) ready to be deployed in real-life remote energy systems? The current system is for various reasons outlined in the report not suitable but it is a fair distance down the path.

Has the testing been sufficient to investigate performance and limitations of the GRIDFORM inverter? Yes, within the limits of an initial investigation and not a full blown engineering test. Missing fault simulation is a key feature to be added to the lab. Deeply rooted bugs can only found through longer term testing. 60% of problems were probably found.

Are the conclusions given based on testing and review correct and adequate? Yes.

What other testing is recommended to ensure viability of the GRIDFORM inverter in a real-life remote energy system?

- Development and review of a fault/failure model.
- Environmental testing.
- Testing under faults.
- Testing within a particular control system framework.