Experiences with Large Grid-Forming Inverters on Various Island and Microgrid Projects

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Abstract **Most Islands and Microgrids are still relying on conventional thermal generation as their primary source to cover their electric demand. Especially in remote locations electricity from PV and other renewable energies can often be produced at lower costs. But relying on conventional generators as the voltage source is limiting the allowable energy share of variable renewable energy sources.**

Large scale grid-forming inverters can act as the backbone for genset-free grid operation and allow renewable energy shares at will. A rising number of projects is proving the concept to work and providing experiences about the impacts on grid operation.

Keywords; grid-forming, voltage-control-mode; island grids; St.Eustatius; field experience; inverter-based grid operation; power quality; grid support; blackstart, resynchronisation

I. BACKGROUND AND TECHNICAL BASICS

Islands and other isolated power systems still mainly depend on thermal power generation from Diesel or other fuels to supply their electric loads. This type of power generation brings a lot of undesired side effects as exhaust gas pollution, noise and a lot of maintenance demand. As plants for solar power generation became much cheaper in the last years, they can help to produce electricity at lower prices and with less environmental impact in those systems.

In PV-Diesel-Hybrid-Systems which are using diesel gensets as voltage and frequency-source, the maximum allowable penetration of solar is limited due to stability reasons (e. g. requirements on minimum load of the gensets etc.). In order to achieve a very high share of PV, it is desirable to be able to switch off the diesel gensets and to provide the grid voltage by utilizing battery inverters. Main benefits of this operational mode are the reduction of LCOE by saving fuel costs and engine maintenance costs, less noise and exhaust gas pollution as well as the possibilities to improve frequency stability and voltage quality.

The grid-forming inverter (GFI) by SMA uses droops for both frequency and voltage amplitude to create the input signal for the actual voltage controller. The droops and the design of the voltage controller are essential for stable parallel operation. The droops are fed with current measurement data, frequency and voltage reference values and both active and reactive power setpoints for easy power management.

Limitations of the battery being connected or other constraints by the inverter hardware are considered before the actual frequency and voltage amplitude signals are applied to the core controller. Overcurrent protection both in hardware and software is the last major element in the design of the grid-forming control.

II. OPERATIONAL EXPERIENCE ST. EUSTATIUS

As presented in [1], SMA Sunbelt Energy GmbH planned and executed a solar and battery storage project on the Caribbean island of St. Eustatius. The project was installed and commissioned in two phases, where the second phase, commissioned in 2017, included large grid-forming Inverters (GFI) with batteries for energy shifting purposes.

Figure 1 shows the schematic setup of the solar and battery storage system as it was completed by phase 2.

In total it consists of 5.2 MVA of battery inverters, 5.77 MWh battery capacity, 3.85MVA of solar inverters and a hybrid plant controller to supply the electrical grid with a peak demand of about 2 MW.

[1] focused on the experiences and results of commissioning and critical site acceptance tests regarding the handling of short-circuit events in the medium voltage grid, load step acceptance and power quality in normal operation.

Since the commissioning in November 2017 the plant is in continuous operation. After one year of operation, the measured operational values were compared with the design targets. The most important KPI is the net-energy fed into the grid. The combined system Phase 1 and Phase 2 had the design target of an energy yield of 6.4 GWh. The measured value of injected energy was 6.49 GWh, this reflects to approximately 1,700,000 liters of Diesel saved and 4,600 tons of CO^2 within one year of operation.

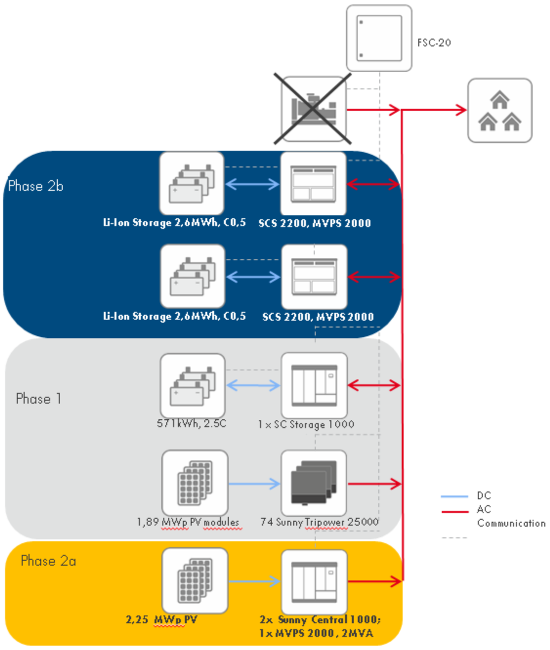

Figure 1: St. Eustatius, the solar and storage system after Phase 2 [1]

The local utility is responsible for the daily operation. SMA Sunbelt provides a remote support on system level, analysis and coordinates technical corrective works, e.g. software updates of the Battery Management System and SMA components. During the first months of operation, several parameters had to be slightly adapted to reduce the generation of warnings and alarms. The system was accidently tested by several disconnections of communication wherein the system could nevertheless continue operation in a safe mode for hours.

Battery performance warranties are based on a defined use case with boundary conditions such as the energy throughput and the temperature. A slight adaption of the SOC range allowed for the system operation was necessary to reduce the cycles according to the defined use case.

The hot-standby function of the GFI in Diesel-On Mode allows to act as an online UPS function for the island grid. Within the first half year of operation diesel generator failures led to a sudden disconnection of the thermal sources in 7 cases and the GFI took over the island's load. These events led prior to blackouts and can be considered as 7 avoided blackouts in the first 6 months of operation.

The GFI in Diesel Off and Diesel On mode had such a significant impact on the voltage and frequency stability of the system that a synchronous condenser that was integrated to the system to ensure the stability is not in use anymore.

The overall experience with the system is very positive and exceeds the expectations. The first months of operation of the very first system of this kind had the character of an announced field test and allowed to finetune and correct parameters, interfaces and functions together with the suppliers. This experience on integration on system level is directly translated in the engineering of new hybrid power plants. Although the St. Eustatius project had a field test character, the system is described by STUCO, the grid operator, as far more reliable than the well-established Diesel genset fleet.

III. ADDITIONAL FUNCTIONALITIES

Since 2017, additional functionalities and power classes of the GFI have been introduced.

One of the major features added is the black start capability both on inverter and plant level. The black start capability allows not only to overtake an existing grid, e.g. from a running Diesel-Genset, but also to be the first generation-asset starting up after a blackout.

From a hardware perspective, this requires the inverter being capable of supplying its internal auxiliaries from other sources than the main MV-power-connection and starting the main inverter from DC power. Auxiliaries can now be supplied from external through 3ph or 1ph-Low-Voltage-AC-Inputs and precharge equipment using the DC-side was introduced.

On a plant level, the functionality of black start must include energization of transformers, paralleling the startup of several inverters in order to allow the start of largely scalable power plants and integration of existing customer installation into the startup process. This functionality is integrated in the hybrid controller, coordinating the startup on plant level.

The coordination of the whole black start procedure takes less than 30sec. As soon as the black start procedure has been finished, the loads in the system may be connected.

Depending on the system status and load demand, after a successful black start there might be the necessity to start conventional generation or to synchronize back to mains. This resynchronization procedure can also be managed by the hybrid controller. Tests show, that a synchronization can easily be achieved within 20sec, leading to transients of less than 1% of the nominal plant power during the coupling event. Once the resynchronization is finished the plant can fulfill whatever control function is requested to be in place during mains parallel operation.

An automatic disconnection of the hybrid grid can also be managed by the hybrid controller. This might become necessary in case of voltage or frequency events from mains to protect sensitive equipment or processes relying on a stable frequency.

In order to be able to remotely manage the transitions between diesel-off-mode and diesel-on-mode, it is necessary to integrate the genset controller system communication wisely into the plant controller. Since each project has a different genset controller model, project engineering for the genset communication interface is vital.

The parallel operation of many grid-forming devices was further improved. The largest project so far includes 7 grid-forming inverters operating in parallel. It demonstrated very low power exchange (<3kVA) to ensure parallelism while also providing fast and equally-loaded response to sudden load changes.

IV. FURTHER PROJECTS EXPERIENCES

In 2018 and 2019 additional projects including large grid-forming inverters were successfully commissioned and brought into operation. A few of them, clustered into comparable applications, are presented in the following.

Typical Island System

Hybrid systems with grid-forming functions have been commissioned for several further islands while respecting diverse technical interfaces such as generator control systems, grid voltages, monitoring systems, existing PV topologies which are briefly described below. A focus and challenge of hybrid system design is the successful integration to the existing local infrastructure. To economically expand the solar energy fraction from 20-30% to >50%, the grid-forming control mode of the battery inverter is a crucial.

Saba island is the neighboring island of St. Eustatius and followed the example of a two phases approach by combining a first power battery application with a solar expansion and an energy battery integration. On Saba Island the BESS is installed in direct proximity of the Diesel power plant, while the PV park is on the other side of the island in 9km distance. Final commissioning was in February 2019.

Table IV.1 Plant information Saba Island

Installed PV power:	2.0 MWp
Installed Storage capacity	2.3 MWh
Diesel capacity:	4.0 MVA
Annual diesel savings:	1,000,000 liters
Island Load:	~ 1.2MW

Tetiaroa, home of the sustainable luxury resort "The Brando" in French Polynesia, has an SMA hybrid system in continuous operation since December 2018.

The two main challenges in the project were the interface to the existing devices (re-powering character) and the integration of the new feature "Black start" into the customers infrastructure to energize the island's transformers solely with the BESS.

The grid of Tetiaroa can now be black started through the new system consisting of the hybrid controller and Sunny Central Storage (SCS). The system can fulfill the service of black start on command and avoids inrush currents of non-energized transformers by performing a softstart from the BESS.

Even with loads already been connected from the beginning the BESS Blackstart reduced the current peak by about 2/3 compared to default energization by just connecting the unloaded transformers to the live genset bus.

Table IV.2 Plant information Tetiaroa The Brando

Installed PV power:	1.3 MWp
Installed Storage capacity	2.6 MWh
Generator capacity:	1.2 MVA
Annual savings:	No information available as fuel mix between Diesel and coconut oil
Island Load:	~ 0.5 MW increasing

While the grid-forming battery power plant is in operation, it brings also substantial improvement of the voltage quality even in parallel operation with the gensets. The total harmonic distortion of the voltages on the MV-bus could be improved from ~4.5% to about ~2.8% as shown in Figure 3.

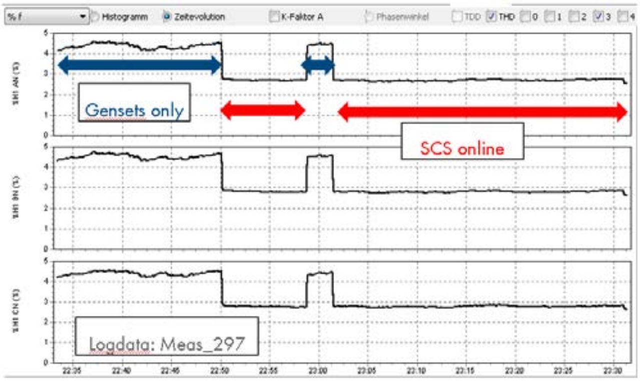

Figure 2: Voltage Harmonics Measurements in the Grid of Tetiaroa Island, measured on the MV-bus 10th December 2018

Grid Support & Resiliency

As grid-tied large-scale battery power plants are becoming more and more popular for providing frequency control services they may also be used for additional services. Using the battery power plant as a backbone for Island operation can allow to operate an isolated grid in case of disturbances in the overlaid grid. This provides improved resiliency to the local supply, allows fully independent operation or gives the option to offer additional services as black start to the overlaid infrastructure.

One example for such a plant was recently realized in Bordesholm, Germany, by RES Deutschland GmbH for the customer and local utility Versorgungsbetriebe Bordersholm GmbH. Incorporating 15 MWh of total battery capacity, the plant is designed to offer 10 MW of Primary Reserve Control to the German Frequency Control Market. [3]

The 7 Sunny Central Storage devices used in this plant are equipped with grid-forming and black start capability.

During the extended commissioning phase, the battery inverters and the enclosed system technology of the whole battery plant were tested for its islanding capability. Black start, Resynchronization, intentional Islanding and sudden grid-disconnection under load could be demonstrated to full customer's satisfaction.

Further References

Another hybrid power system using large scale grid-forming battery inverters of SMA was commissioned on the island of Graciosa with system integration done by Greensmith Energy – a Wärtsila Company. The Graciosa Hybrid Renewable Power Plant integrates 1 MW of solar power generation and 4.5 MW of wind power generation by using 3 Sunny Central Storage 2475 with grid-forming and black start capability. [4]

Both its flexible usage by allowing parallel operation with different types of power sources and its control interface allowing easy integration of black start and synchronization of different grid parts were proven successfully.

V. LEARNINGS FROM PROJECT EXPERIENCES

From the variety of projects with grid-forming functionality in use a lot of experience was gained.

Experiences in parallel operation with different energy-sources ranging from comparable small Diesel-Gensets (smallest of ~125 kVA) to the public grid demonstrated the grid-forming control being mature for a wide variety of application.

Integrating GFI in typical genset-based island-grids is mostly driven by achieving higher penetrations of renewable energy sources. But they may bring a lot of additional advantages to the operation of the system. Improved voltage harmonics, reduced inrush-currents and the online UPS-capability were already explained.

Other side-effects became obvious while operating the island's grids only on inverter-base: By switching off the ancillary components of thermal generators as cooling fans and fuel pumps, the total energy consumption might also be significantly reduced.

As BESS plants offering grid-forming capability in island grids are integrated in existing power systems, most projects require a lot of related engineering services and customizations. Even when the technical solution is mature, the project specific integration is an important work to be considered.

In several projects the connection of non-energized load sections became a topic to be intensively discussed. While the black start of the power plant transformers often is in the focus of project planning, energizing the load sections mostly isn't. Sudden connection of non-energized load sections is feasible up to a certain ratio of the generation capacity. But the inrush currents might result in voltage distortions.

Figure 3 shows the setup for a test of a sudden energization of two transformers by one inverter in an isolated grid. The transformers are all of 2.5MVA nominal rating.

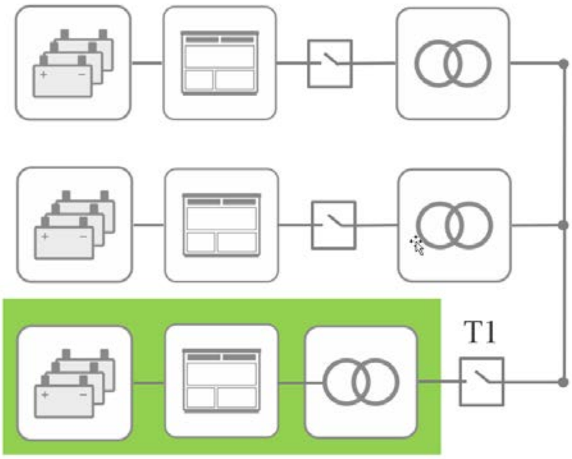

Figure 3: Setup Schematic for energization test of 2:1 ratio of transformers against generation

Figure 4 shows waveform measurements of AC Voltages and Current of the test as drafted in Figure 3. T1 is the switch being closed during the test. As Inrush currents heavily depend on the pre-magnetization and phase-angle during breaker-closure this could act as an example but as a general behavior.

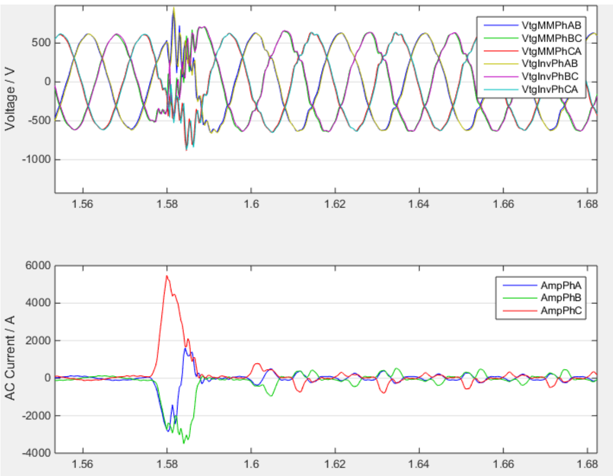

Figure 4: Energization test of 2:1 ratio of transformers against generation; waveform measurements of AC Voltages and Current at the Low-Voltage Inverter Output

This measurement shows that the inverter could energize the two transformers. The energization not only requires a lot of inrush current, but also creates some short-time distortion on the voltages.

While this test was successful, the ratio of transformers against inverters is usually recommended to be 1:1 or lower in order to avoid high inrush currents, voltage distortions and possible disconnections due to protective equipment been triggered. Detailed sequencing of transformers or integration of the transformers into the softstart procedure of the BESS help to achieve better voltage quality during energization.

VI. OUTLOOKD AND PORTABILITY TOWARDS THE PUBLIC GRID

Some current medium and high voltage grid codes [5] stipulate, that in case of grid faults DER must feed in a dynamic reactive current in order to support the grid voltage in the area around the grid fault. State of the art is, to define a “k-factor” representing the proportion of the amount of additional reactive current to be fed into the grid and the change of voltage during the fault relative to the pre-fault voltage, approximating the behavior of a synchronous generator.

Ideally, during the operation of a grid-forming inverter (as well as the operation of a synchronous machine), the additional current and power flow to the grid in transient situations depends on the difference between the voltage vector of the inverter, the deviating vector of the grid’s voltage and the coupling impedances. If the grid’s voltage changes suddenly in amplitude, phase or frequency, an inherently stabilizing current flow occurs, which’s change in amplitude and phase angle depend on the impedances and on the steady state operating point before the fault. Thus, the resulting advantageous current flow is not necessarily predefined uniquely by the above mentioned k-factor.

Detailed investigations about a favorable behavior of grid-forming inverters during a fault in interconnected grids are still ongoing. From a power system’s point of view, it can be assumed, that robust ride-through, a good support of the retained voltage at the point of common coupling in case of distant grid faults as well as robust synchronization after the fault should be criteria in order to evaluate control technologies rather than an exact current-defined behavior as it is defined today. This should be kept in mind when grid codes are specified in the future in order not to become an obstacle for grid-forming control technologies.

Even though GFI bring advantageous support to the grid, grid-forming capability is presumably not generally required for all inverter-coupled DER. Usually inverter-coupled DER with renewable primary resources are desired to feed in their maximum available power and in normal operation don’t provide headroom for inherently provided additional active power. With an expected increasing share of battery systems in mind, they may be a good target application system for this type of control providing additional services to the grid.

It can be expected, that such systems, distributed at medium and high-power levels, can help effectively to stabilize an electric power system consisting of distributed energy resources in case of grid faults, system splits and sudden load steps. It should be noted, that such services from battery-equipped DER have the capability to replace so-called “must-run-units” in the grid and can allow 100% inverter-based grid-operation as demonstrated in the power system of St. Eustatius.

In addition, with voltage control mode inverters new possibilities arise to improve the operating ability after a system-split of distribution networks and to incorporate DERs into grid restoration.

Conventional grid-tied inverters use the measured grid voltage as a reference for controlling their output current accordingly. Under low short circuit ratio (SCR) conditions this control method can potentially cause oscillations due to a feedback effect in case the inverter has a high influence on magnitude and phase of its terminal voltage.

GFI primarily control their output voltage and thus avoid this effect. Furthermore, they can increase the SCR in the area of the grid they have been installed to. The stability added is comparable with synchronous condensers but with the advantage of offering additional grid services and less wear and losses since, except for fans, no moving parts included.

While synchronous condensers can only be used to increase stability and for reactive power provision a GFI system can participate in additional markets (e.g. frequency control, short- and long-term storage, etc.) und thus have a significant advantage due to its profitability.

VII. ACKNOWLEDGEMENTS

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The authors are responsible for the content of this paper.

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BIOGRAPHICAL INFORMATION

Oliver Schoemann is born in Blieskastel/ Germany 1987. From 2008 to 2012 he studied renewable energies at the “Hochschule für Technik und Wirtschaft Berlin” and achieved a Bachelor of Science degree. From 2012 to 2014 he studied electrical engineering at the “Universität Kassel” and achieved a Master of Science degree.

He works in development and testing in SMA Solar Technology AG since 2013. Currently he holds the position of System Test Development Engineer in the department of Test & System Integration.

Mr. Schoemann joined the team which developed the first central battery inverter produced by SMA. Currently he is mainly involved in functional qualification and system integration tests for large-scale storage-inverters and plant-controllers.