Switching off the Generator – the Stable Operation of Sustainable Island Grids in the MW Range Using Renewable Energy and Energy Storage

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Abstract

While increasing the share of renewable energy to 20% is a challenge for the stability of the grid, working towards a 100% renewable energy supply requires completely new approaches. Small island grids are the ideal platform to start realizing tomorrow's energy concepts today. To develop the necessary technologies, a test site at the medium voltage level was established in Berlin. The approach by Younicos, results of the test phase and key parameters of the pilot project will be summarized in this paper.

1 Introduction

Countries across the world have set the goal of increasing the share of renewable energy (RE) to 20% by 2020 and even higher in the longer term, in order to ensure their energy supply is sustainable. Taking this further, the energy supply in 2050 could be more than 50% renewable and thus the majority would be from RE. While increasing the share of renewable energy to 20-30% is a challenge for grid stability, pushing this share to 50% and beyond requires new approaches [1][2]. The relationship between the share of renewable energy and the grid stability is shown schematically in **figure 1.1**.

1.1 Problem: Grid Stability with a High Share of Renewable Energy

Grid stability is currently maintained by conventional power stations. This means that these power stations remain on the grid, even if wind and solar energy could cover the electricity demand in a grid at a given point in time. Consequently, the wind farms and solar power plants are powered down. However, this limits the share of the energy supply that could come from RE. Energy storage systems are required to be able to lift this limit, as they can take over the role of controlling the grid and allow the conventional power plants to be switched off.

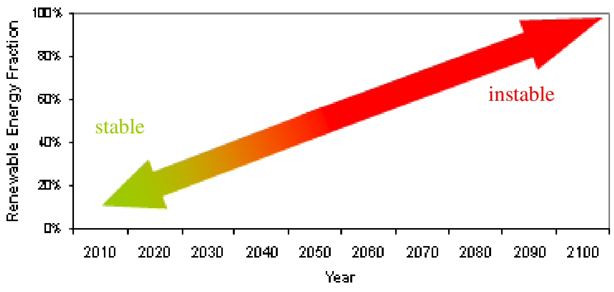

Figure 1.1 Schematic illustration of the relationship between grid stability and the share of renewable energy

Island grids in particular are already at this limit. Installing just a few wind turbines or one solar park is often enough to reach the technical limits of the grid. In addition, the cost of electricity from diesel generators – which provide the majority of the energy in independent grids – is rising constantly due to the development of oil prices. Establishing new energy concepts that will allow a departure from fossil fuels is therefore particularly interesting from an economical point of view for self-sufficient supply structures.

1.2 Goal: Stable Generation System with Renewables and Energy Storage in the Megawatt Range

The goal of Younicos is to develop technical solutions to realize the vision of an energy supply that primarily relies on RE. Wind farms, solar parks and, increasingly, energy storage systems are available on the market. Control solutions need to be developed that allow stability in a grid based exclusively on decentralized, renewable generators and storage capacity in the MW range. Storage management, intelligent power electronics and the development of a top-level energy management system all play an important role.

2 Technical Challenges

2.1 Status Quo in Grid Stability

The rotating mass of synchronous generators, used in conventional units such as diesel generators, acts as short-term storage in the grid, since the inertia absorbs all deviations from the operating point. The machine is speeded up or slowed down, depending on whether a step in the load is positive or negative. The resulting change in frequency is registered by the controllers in the power plant and is countered by adjusting the power output. In this way, the inertia of the generators acts to stabilize the grid. Further-more, a generator is capable of briefly providing a current level that is several times its nominal output. This performance is usually the basis for grid protection. In the event of a fault, the affected branch will be disconnected by activating overload protection.

2.2 Challenges for New Generation Structures

If these power plants were now to be disconnected from the grid, the remaining units in the grid – renewable sources and storage systems – would have to take over these tasks in addition to generating energy.Since both renewable sources and batteries are connected to the grid via inverters, the properties of the synchronous generators are no longer available to stabilize the grid. While supply structures based on fossil fuels are often characterized by fewer, centralized units, renewable sources in a decentralized supply structure are much smaller and spread out over the supply area. In grids with limited short circuit power, the behavior of the decentralized power plants in the event of a short circuit becomes particularly important. The diesel generators commonly used in island networks are able to briefly deliver several times their nominal power, guaranteeing that the protection equipment is activated. Inverters are normally limited to their nominal power. However, the battery inverters must assume the generators' functions, if the latter are switched off.

In summary, the following requirements must be fulfilled by a new generation structure, in order to guarantee the supply security and power quality for island grids, as stipulated in EN 50160.

- **Frequency and voltage** must be regulated according to the requirements of the standards for **power quality**, in terms of the permissible tolerance band and quality requirements
- **Power balance** – the power must be kept in balance, despite fluctuating generation, at all times through reliable cooperation between the components, in order to ensure **grid stability**
- **Energy balance** – the use of renewable energy sources should be maximized without risking the **supply security**
- The participants should be connected via uniform **communication standards**, in order to enable the generation park to be extended without problems
- Sufficient **short circuit power** must be available in the event of a short circuit, in order to activate existing circuit protection

3 Approach

Younicos has implemented a concept for the stable operation of renewable island grids without rotating generators. With regard to the control concept, a distinction is made between decentralized and centralized control requirements, as shown schematically in **figure 3.1**.

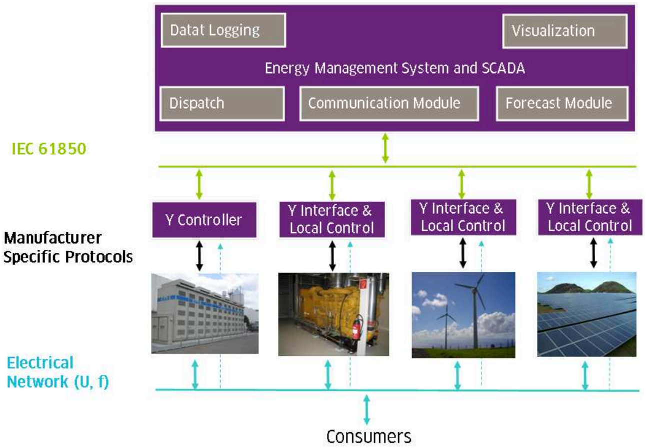

Figure 3.1 Concept for controlling island systems

The aforementioned requirements of a renewable supply structure are addressed here below.

3.1 Decentralized Controllers for the Control of Frequency and Voltage to Guarantee Grid Stability and Power Quality

The decentralized controllers ensure that the instantaneous power is balanced out, thus securing stability. To decouple the availability of the grid from the availability of standard communications media, the components in the grid have sufficient intelligence to guarantee stable grid operation at all times. This is performed by local controllers, which react independently and carry out stabilizing tasks where time is critical, in the range from µ-seconds to seconds.

Voltage and frequency control

Powerful computers in the battery inverters control the frequency and voltage with speed and accuracy. This allows the inverter to take over the function of the controlled voltage source. Unlike with rotating machines, the grid frequency is not physically changed by the machine slowing down or speeding up when the fed-in power changes. Rather, it is modulated by control algorithms according to the requirements in the grid. In particular, the relevant standards for voltage quality, such as the tolerance bands defined for island grids in EN 50160, can be met.

Primary control is implemented using power-frequency curves in the decentralized controllers. These lead to a controlled stationary deviation in the frequency. Amongst other things, this enables voltage sources to be operated in parallel. Secondary control of the frequency, which allows a return to the nominal frequency, can be implemented at the central level of the energy management.

Power balance and grid stability

The battery inverters play a central role, because they are responsible for the instantaneous power balance and compensating for fluctuations by charging and discharging the battery.The resulting deviation from the nominal frequency, which is determined by the operating state of the battery, is visible in the entire grid and indicates the amount of available energy in the grid. Therefore, other participants in the grid can react accordingly. While renewable generating units can adapt what is fed in, intelligent loads can react with a change in the consumption. By using the frequency as a communications medium, the grid operation will remain stable – if, perhaps, suboptimal – in the event of a disruption to the wireless or cable-connected communications networks between the decentralized components and the energy management.

3.2 Central Energy Management for Supply Security and Optimal Operation

As the central intelligence, the energy management is responsible for the optimal operation of the grid. It ensures that the energy is balanced, guaranteeing long-term supply security and battery management. Due to the capacity of the batteries, the processes controlled by the energy management are not critical in terms of time, i.e. the grid stability is, in principle, ensured by the decentralized controllers, even without the energy management system acting.

Energy balance and supply security

The dispatch schedule is optimized with the goal – aided by forecasts – of guaranteeing long-term supply security, maximizing the share of renewable energy and minimizing the electricity generation costs. The battery system plays a central role in the dispatch schedule, since it compensates for the unavoidable fluctuations in the generation of electricity with renewable generators.

The time horizon for the control tasks of the energy management system lies in the range from minutes up to several days. The energy management also includes the standard management functions, such as data logging, data visualization and warning and alarm management.

Standardized communication interface

For communications, the central unit is connected to all units in the electricity grid via cable or wireless networks. The connection at the energy management level is made with interfaces standardized in IEC 61850. This standard is currently establishing itself in both classic distribution network and "smart grid" applications. Local communications adapters are being developed for the different components so that the protocols supported by the different component manufacturers can be converted to the IEC standard. This makes plug-and-play integration possible between the components and the energy management system.

3.3 Providing Short Circuit Power for Safe Grid Operation

If a fault occurs in the grid, a sufficiently large short circuit current has to be provided by the battery inverters, in order to activate the protection equipment. The inverters also have to be protected from an overload. By controlling the inverters quickly enough, the short circuit currents can be controlled in the event of a fault to fulfill both of these requirements.

4 Island Test Bay

Younicos has set up a test bay in Berlin to develop and optimize the hardware and software required. All power flows occurring in a self-sufficient supply grid can be simulated here. The island test bay includes the components in an energy supply system and the equipment for implementing test scenarios based on load measurements and meteorological data from a specific location. The topology of the system and its core components are explained below.

4.1 Layout of the Test Bay

The system has been laid out, as shown in **figure 4.1**, to be similar to typical topology for small island grids.

4.2 Function and Performance Data for the Core Components

The functions and performance data of the core components are explained below.

(1) Diesel generator – 1 MW
The diesel generator represents the conventional form of energy generation, as used currently in the majority of island grids that are not connected to the mainland by undersea cable.

(2) Photovoltaic plant – 210 kW
The photovoltaic plant can be connected to the test bay to investigate the influence of its fluctuating supply on the whole system.

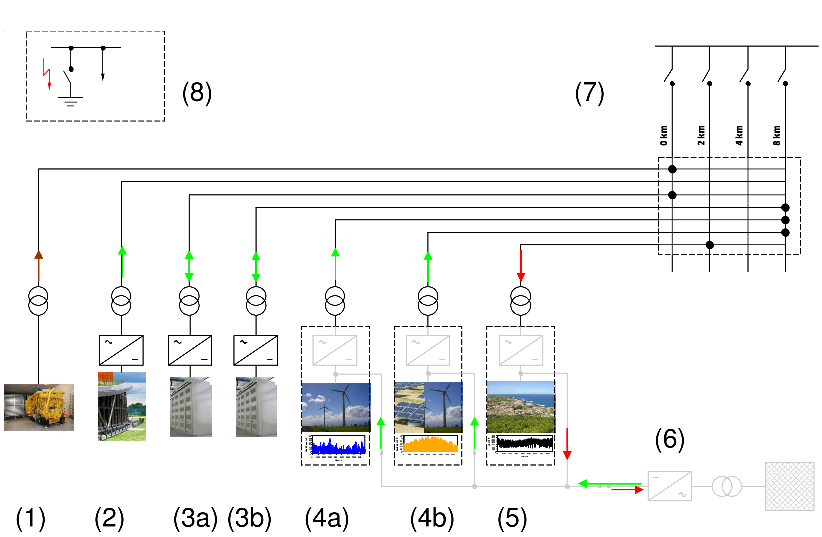

Figure 4.1 Layout of the Island test bay

(3) Sodium-sulfur (NaS) battery – 2x 500 kW/3 MWh
The battery system, shown in **figure 4.2**, consists of two separate battery blocks, each 500 kW/3 MWh. The properties of the NaS battery system are summarized in the following overview [3]:

- Power: 2 x 500 kW
- Short circuit current: 4 x In
- Capacity: 2 x 3 MWh
- AC efficiency: 75%
- Service life: 4500 full cycles, 15 years
- References: 300 MW worldwide
- AC reaction time: <100 ms
- Operating temperature: 300 °C

Figure 4.2: NaS battery in Berlin

(4) Source simulators – 2x 1 MW
The dynamic response of wind turbines or photovoltaic plants can be simulated with the help of these inverters. The simulators use mathematical models of wind turbines and photovoltaic plants as input data, as well as high resolution climate data.

(5) Load simulator – 1 MW
This inverter serves to simulate the load response on an island. Measurements of consumption are used here for reference settings.

(6) Auxiliary Supply
Depending on the mode of operation, energy can be drawn from or fed in to the public supply grid for the operation of the simulators. The island grid is decoupled from the main grid in terms of voltage and frequency via a DC coupling, giving the maximum flexibility for carrying out test trials.

(7) Medium voltage grid
In grids with a connection power in the order of several MW the electricity is usually transported via a medium voltage distribution network. In order to take this into account, a 15 kV medium voltage grid has been installed, including switchgear, transformers and a simulator for power lines 2-8 km long.

(8) Short circuit switch

A short circuit switch has been installed in the system, allowing specific short circuits and ground faults (one, two or three phase) to be generated in the medium voltage grid. With its help, protection concepts and the system response in the event of a fault can be analyzed and optimized.

5 Test Results

The results of an example of a sequence carried out in the test bay – based on measurement data for the load, wind and irradiation – are given here. **Figure 5.1** shows the development of the frequency (top) and the power (bottom) of all operating units.

The following units are used in the test: battery inverter 1 (green), battery inverter 2 (red), electrical load simulator (gray), wind simulator (light blue), photovoltaic simulator (blue) and the diesel generator (yellow). The frequency is controlled within the tolerance band from 49 to 51 Hz (EN 50160 for island grids) throughout the entire test. If the batteries are being charged, the battery inverters set a frequency above an adjustable reference frequency and use a lower frequency for discharging. As can be seen at the beginning and the end of the test, the reference frequency is 50.2 Hz at zero-load.

Figure 5.1 Development of the power and frequency

5.1 Regular Operation

At the start of the test (section A), the grid consists initially of one battery inverter. After connecting the load inverter, the second battery inverter is synchronized to the grid. As soon as battery inverter 2 is on the grid, it takes over half of the load. In section B of the test the wind turbine and photovoltaic simulators are connected. If the energy provided by the renewable sources is not sufficient to cover the load, the batteries will continue to be discharged. As soon as there is excess energy from the renewable sources, the batteries will be charged. When charging, too, the batteries share the energy evenly. The transition from charging to discharging and vice versa is instantaneous.

In the next stage (section C), the batteries are assumed to have a low charge state. The diesel generator receives the instruction to synchronize to the battery grid. If the diesel generator is on the grid, it shares the load with the batteries according to the settings of its controller. With a differently selected parameterization of the power-frequency curves, the batteries could alternatively be charged by the diesel generator. The diesel generator can be switched off again without any disruption, as can be seen toward the end of section C.

5.2 System Reaction to the Failure of Generating Capacity

A special case in the supply of electricity is the sudden failure of generating units (here: the renewable energy sources). It can be seen in section D, shortly before the point of the dropout of the renewable energy sources, the entire load (approx. 500 kW) is supplied by the renewable energy sources and the batteries are being charged with around 500 kW. The dropout of the renewable energy sources (due to the failure of a power line, for example) is compensated for instantaneously by the batteries. The batteries swap from charging at approx. 500 kW to discharging at -500 kW.

5.3 Operation in the Event of a Short Circuit

Another special case in the electricity supply is the occurrence of a short circuit. The voltages and currents at the 0 km cable outlet, i.e. directly on the central bus bar (see **figure 4.1**) are shown in **figure 5.2**. When the short circuit is connected the voltages collapse and the short circuit current builds up. Short circuit currents 3.5 times the nominal current are reached.

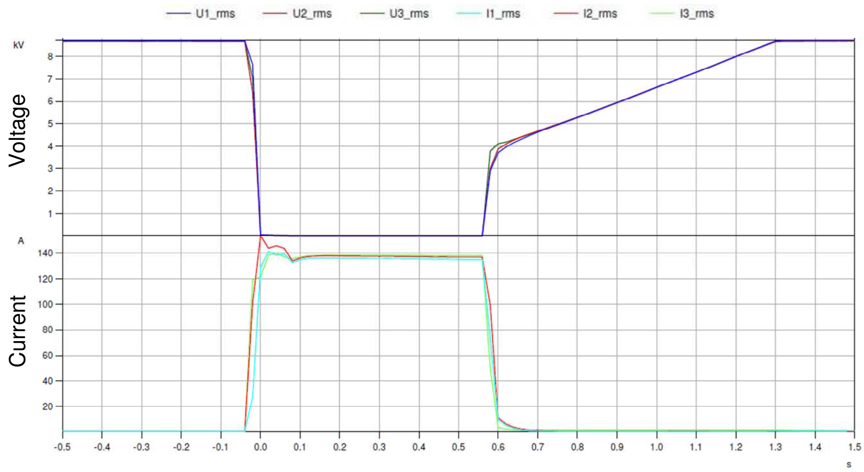

Figure 5.2 Voltages and currents during a short circuit

Depending upon the parameterization of the protection devices, the protection equipment for the circuit breaker recognizes the short circuit and activates. The short circuit is switched off approx. 600 ms after it started. The nominal voltage in the grid is restored after around a further 700 ms. The voltage ramp is chosen deliberately here to keep inrush currents low. With the inverters used in the test bay, short circuit currents up to 4 times the nominal current can be implemented for up to 3 seconds. The layout must be adapted to the conditions of the grid in individual cases.

6 Graciosa Pilot Project

Economic studies show that energy systems, where the majority of energy is fed in by renewables and batteries, can be competitive with a supply provided fully by diesel generators. This is due to the high maintenance and fuel costs for diesel generators, to which the transport costs of the fuel to remote regions also have to be added. Currently, the conditions that justify operating an energy system with up to 100% renewable sources both ecologically and economically are limited to locations that are not connected to larger grids. These are locations such as small islands and settlements far away from the grid.

A pilot project is to be implemented on the island of Graciosa. With 4500 inhabitants and an area of 70 km^2, Graciosa is one of the smaller islands of the Azores. The peak load is around 3 MW, with an annual electricity consumption of approx. 14 GWh.

Figure 6.1 Graciosa island

Currently, around 85% of the electricity required is generated by diesel units; 15% is generated by an existing wind farm. The government of the Azores has set the political goal of providing 75% of the electricity supply with renewable energy sources by 2018. The energy provider in the Azores, EDA, has already implemented different renewable energy sources on the islands – from hydropower to geothermal to wind.

Together with EDA, Graciosa was identified as a candidate to lead the fulfillment of the political goal by supplying 75% renewables with the help of wind, photovoltaics and batteries. The layout of the future energy system on Graciosa is shown in **figure 6.2**

In this project, Younicos has the role of the project developer, including the layout, system simulation and system planning, as well as commercial and legal project development. The project is currently in the contractual and approval phase. It should be implemented from 2012 onrds. Younicos is acting as the turn-key supplier for the hybrid system and the integration with the existing power system.

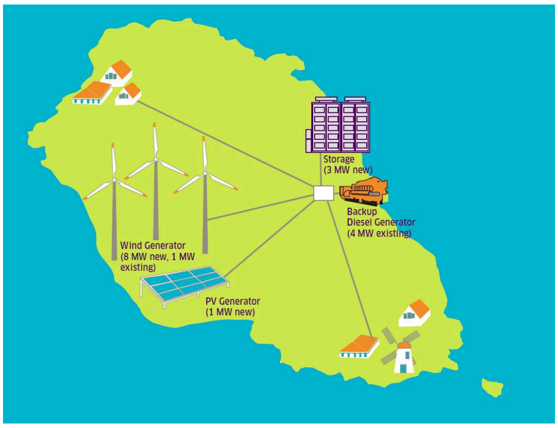

Figure 6.2 Future generation structure on Graciosa

7 Outlook

The ability to switch off the diesel generator, i.e. guarantee a stable grid exclusively using fluctuating sources and batteries and without rotating masses, gives the freedom to actually choose any configuration between 0% and 100% renewables. Thus, the optimized system layout can be set up according to the ecological and economical goals alone and not what is technically possible.

With increasing costs for raw materials and a raised awareness about sustainable energy supplies, this kind of a decentralized supply concept will also be interesting for regions within the national grid that wish to increase the amount of electricity generation coming from renewable resources.

8 References

[1] Brodersen, N.; Nabe, A.: Stromnetze 2020 plus, Gutachten im Auftrag der Bündnis 90/Grüne, 2009

[2] ETG Task Force Energiespeicher: Energiespeicher in Stromversorgungssystemen mit hohem Anteil erneuerbarer Energieträger, Verband der Elektrotechnik Elektronik Informationstechnik e.V., 2008

[3] Mizutani, T.: Innovative Technological Developments in Electricity Storage, Hannover Messe - World Energy Dialogue, 2009