Achieving an Annual Wind Penetration of 20% on an Islanded Distribution Network

Konstantinos Pierros
Sales – Grid Integration
ENERCON GmbH-UK
Edinburgh, UK

Nathan Coote
DSO & Innovation
Scottish and Southern Electricity Networks
Shetland, UK

***Abstract*—Shetland is the largest electrically isolated power system in the UK. Despite the excellent wind resource, frequency stability concerns resulted in the limitation of annual wind energy penetration to just 7% of total Shetland system demand. Focusing on transitioning to a low carbon network and evaluating how this can be securely operated with a high penetration of renewable generation, Scottish and Southern Electricity Networks (SSEN) developed and delivered the innovative project "Northern Isles New Energy Solutions" (NINES) between 2010 and 2016. As a result of this project, the total renewable generation capacity trebled to over 12MW, following the installation of seven type IV ENERCON Wind Turbine Generators (WTGs) at three sites. The Shetland system is on track to achieve 20% total wind penetration in 2017-18, which corresponds to approximately 40GWh annually. Such isolated power systems can function as a microcosm for the conditions likely to be encountered in the near future in more complex systems. This paper shares valuable experience of operating the power system on Shetland with a high penetration of renewable generation including resilience to grid events, response to active and reactive power setpoints and the management of high wind speed events.**

Keywords–Shetland; Northern Isles New Energy Solutions; Active Network Management; Isolated System; Islanded System; Type IV Wind Turbine Generators; Wind Penetration

I. INTRODUCTION

The United Kingdom ranks amongst the top places in Europe for both onshore and offshore wind resource [1]. As a result of national and international targets including the EU Renewable Energy Directive, energy from renewable energy sources, particularly from wind, has been steadily increasing since 2000 [2]. Renewable energy (solar photovoltaics, onshore and offshore wind, bioenergy and hydro) provided 24.5% of the electricity generated in the UK in 2016, whilst onshore wind reached almost 11GW of installed capacity and accounted for 25.2% of the total renewable generation [2]. State-of-the-art solar and Wind Power Plants (WPPs) are non-synchronous (connected to the electrical network via power electronics) and therefore come with a new set of characteristics with respect to their grid performance. Considering also the changes in the patterns of demand, the increasing penetration of non-synchronous generation will pose new challenges to the GB System Operator (SO) and the Distribution Network Operators (DNOs).

In response to this, it is valuable to observe isolated systems already experiencing a significant non-synchronous penetration, as they can function as a microcosm for the conditions likely to be encountered in the near future in larger, more complex and perhaps more demanding systems as levels of non-synchronous penetration increase. Amongst such power systems the Shetland Islands offer an excellent case-study.

Shetland is the largest islanded power system in the UK supplying a population of 23,000. The islands have a winter maximum demand of 45MW and a summer minimum demand of 12MW. Despite an enviable average wind capacity factor of 52%, only 7% of the total demand was generated from wind each year, with further business-as-usual connections limited to 3.68kW per phase. From 2010 – 2016 Scottish and Southern Electricity Networks (SSEN), the SO of Shetland, ran the innovative project "Northern Isles New Energy Solutions" (NINES). Its core objectives were to reduce reliance on fossil fuel consumption and to evaluate how an isolated distribution network could be securely operated with a high penetration of renewable generation. The project trialled a smart control architecture including Active Network Management (ANM), energy storage, domestic demand side management and flexible generation contracts – where generators accept network-specific connection conditions such that their output may be curtailed to maintain system stability, without financial compensation. The ANM system architecture for NINES required a robust, reliable platform capable of controlling both generation and demand sources.

The legacy of the project has trebled the total renewable generation capacity on Shetland to over 12MW. This was achieved following the installation of seven type IV ENERCON Wind Turbine Generators (WTGs) at three different projects with a total installed capacity of 8.4MW. The electrical performance characteristics of this non-synchronous generation combined with controls at the Point of Connection (PoC), offer an additional degree of flexibility that can be valuable in operating small, non-interconnected systems. The Shetland system is on track to achieve a total wind penetration of 20% in 2017-18, which corresponds to approximately 40GWh annually.

This paper begins by introducing the challenges of integrating non-synchronous generation in an isolated system. Details of the innovative NINES system on Shetland are introduced, followed by a summary of key electrical capabilities of type IV WPPs. Finally, valuable experience of operating the Shetland system with a high penetration of renewable generation is shared.

II. Challenges of Integrating Non-Synchronous Generation in An Isolated System

Maintaining stability on an islanded system with a high penetration of non-synchronous renewable generation presents a number of technical challenges. This section briefly discusses the most prominent ones.

A. Declining System Inertia

Replacing conventional synchronous plant with non-synchronous renewable generation reduces the amount of system inertia. While non-synchronous generation is capable of providing a synthetic inertial response, as shown in section IV, the characteristics of this response might not always fit the current operational strategies of the SO in question. As a result, the likelihood of frequency instability might increase, together with the potential impact of underfrequency load shedding during fault conditions [3].

B. System Balancing

It is well understood that non-synchronous renewable generation has a variable output that depends on the weather conditions. In the absence of other providers of flexibility, the increasing penetration of non-synchronous renewables will likely result in the increased need for spinning reserve to meet any shortfall between generation and demand to keep the system balanced. Under these scenarios, operating the system becomes more technically and economically challenging, with an increasing risk of rising cost for the provision of related ancillary services [4].

C. Voltage Rise

The installation of distributed generation on rural networks may lead to voltage rise due to the lower X/R ratio – particularly towards the end of a feeder, during times of high active power output and corresponding low local demand [5]. In an attempt to keep the voltage within statutory limits, local on-load tap changing transformers would operate significantly more frequently – due to the variable output of this generation and the associated change in power flows. This may result in increased wear of components or even higher voltage levels. To counteract this, distributed generators can be required to provide voltage control: absorbing reactive power in the event of increased voltage and injecting reactive power when the voltage reduces. A prerequisite for the provision of voltage control is that the distributed non-synchronous generation is capable of exchanging reactive power with the network, either on its own or through dedicated “Flexible AC Transmission System” (FACTS) solutions, like STATCOM units.

D. Protection Settings

Protection systems help minimise the danger to persons and equipment in the event of fault conditions. Isolated systems with a lower level of system inertia may not be able to control the system frequency within the narrow operating ranges experienced in larger power systems and might experience higher Rate of Change of Frequency (RoCoF). This might increase the frequency of operation of protection in response to network events. Protection settings must be set according to specified standards and in some cases according to legal requirements. In isolated systems, such protection settings need to be even more carefully selected, reflecting the need to minimise nuisance tripping that could lead to frequency instability, whilst protecting against the risk of unintended islanding of parts of the network. For example, in the case of generation connected to the UK distribution networks, the voltage, frequency and loss-of-mains protection settings are set according to the Engineering Recommendation (EREC) G59/3 and protect both the generating plant in the event of a network fault, and customers against the generating plant operating islanded. Reflecting the impact the increased penetration of renewables has already had on frequency control, the EREC G59/3 amended the loss-of-mains setting from 0.125Hz/s to 1Hz/s (with a 0.5s delay) [6].

E. High Wind Speed Events

The effects of high wind speed events on isolated systems might be exacerbated due to the limited spatial variation of the wind speed; most isolated systems are islands with a relatively small area, meaning that selected sites will experience similar wind speed variations. As a result, the performance of the WTGs during high wind speed conditions becomes more important. High cut-out wind speeds are beneficial to the security of supply, but this should be combined with a controllable and smooth reduction of active power output. Fast active power changes should be avoided, since they might result in increased wear on synchronous machines and might even introduce frequency instability to the network.

III. NINES – Shetland’s Innovative Project

A. Background

110 miles northeast of mainland Scotland, Shetland is the largest islanded power system in the UK. With no form of interconnection, all generation and demand must be balanced locally by SSEN. Prior to 2014 there were three main generation sources:

- Lerwick Power Station (LPS): a 67MWe oil-fired plant.
- Sullom Voe Terminal (SVT): four gas turbines, each de-rated to 20MW, which power the oil and gas terminal. An export-only power purchase agreement is in place with SSEN to supply 5-15MW during normal operation.
- Burradale WPP: a type II WPP with a capacity of 3.68MW.

In 2006 Burradale WPP and other microgeneration had reached a capacity of 4MW of “firm” wind – where all units generated must be accommodated by the system, regardless of demand. Modelling and analysis of the Shetland network by the University of Strathclyde detailed that the potential loss of wind during an outage of SVT would result in an unacceptable frequency deviation. The report concluded that no more firmly-connected large wind generation could be accepted on to the Shetland network. Further business-as-usual connections for renewables were limited to 3.68kW per phase.

B. NINES Business Case

With traditional network reinforcements years away and significant demand from WPP developers looking for a connection, SSEN had a strong business case for an innovation project. The transition to a low carbon network would require more than one solution and NINES provided an opportunity to trial several, at a scale that would generate statistically relevant learning for the whole energy sector of the UK. NINES was approved as the first phase of a Shetland repowering project and was expected to inform the design of a replacement power station in Shetland.

C. System Architecture

The architecture of the ANM system on Shetland built upon an earlier ANM deployment on the islands of Orkney which are interconnected to the UK mainland and have 25MW of generation under real-time ANM control. However, the islanded network of Shetland also required the design of NINES to be capable of controlling demand sources. In addition, the constraint management rules required were very different: Orkney’s rules centred on thermal and voltage limits particularly for the submarine cable link to the mainland, whereas Shetland’s rules focused on network stability, ensuring at any time that the permitted level of ANM controlled generation did not compromise this. A logical overview of the system architecture is shown in Fig. 1.

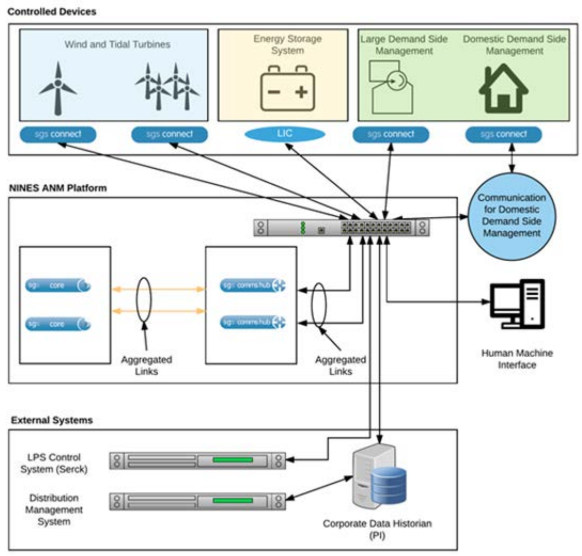

Figure 1. High level overview of the NINES architecture

The main components of the system include:

- SGS comms hub: a communication gateway that is hosted on two servers to provide resilience to a single point of failure and has installed applications which facilitate all data exchange.
- SGS core: a further two servers with applications which host the control algorithms responsible for all constraint management and device scheduling calculations.
- SGS connect: Local Interface Controllers (LICs) installed at each site, communicating both with the ANM system and the generator Local Control System (LCS).

Fig. 2 shows a high level overview of the electrical and communication connections between the ANM and each generator on Shetland. The LIC is responsible for collecting data including current, voltage, active power, reactive power, wind speed and direction. It also issues upper load setpoints and commands, such as in or out of service, and also runs with a fail-safe logic in the event of a communication fault both upstream and to the LCS.

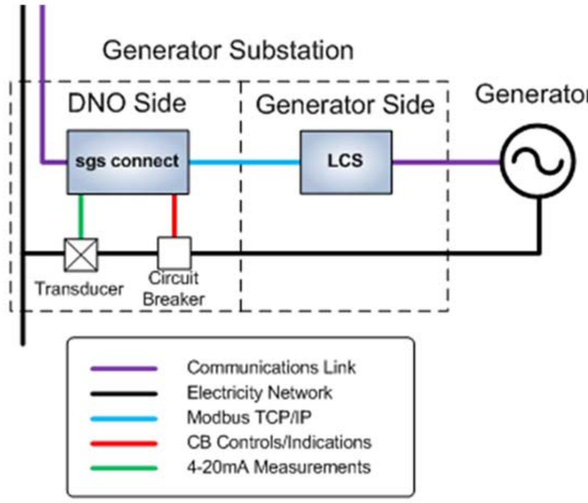

Figure 2. Electrical and communication connections between the ANM and each generator

D. Energy Storage

SSEN installed a Battery Energy Storage System (BESS), consisting of Valve Regulated Lead-Acid (VRLA) modules with a total rated power of 1MW and a total energy rating of 3MWh. The BESS was integrated with the Shetland ANM system for scheduling, monitoring and control. During the trial the BESS was primarily used for load shifting and alleviating renewable generation constraints. It completed close to 500 cycles, discharging 1.5GWh and charging 2GWh for a round trip efficiency of 75%.

E. Demand Control

The Shetland ANM is capable of controlling other demand sources. A trial of next generation storage heaters and hot water cylinders took place. Rather than a fixed charging schedule provided through the radio teleswitch system, schedules were calculated by the ANM system, based on system demand and renewable generation output. This was achieved through an intermediate system, Element Manager, which collated daily energy requirements from individual devices and presented this to the ANM system as group requirements. The ANM schedules for these groups were calculated daily and could be updated intra-day if a change in conditions triggered a recalculation.

F. Flexible Generation Connections

In addition to new technical solutions, the NINES project trialled new commercial solutions; generators connecting to the Shetland network under NINES were offered a flexible generation connection, whereby their output may be curtailed in response to network conditions to maintain system stability. There would be no financial compensation for curtailment and generators had no guarantee regarding their level of grid access. SSEN conducted a curtailment assessment for each generator and provided an estimated level of curtailment. While this was provided in good faith, it was emphasised that this was just an estimate, leaving generators to assess the risk before making an investment decision. A queue was formed in the order that acceptance of the Connection Offers were received. Generators would be curtailed based on the “last in, first out” principle of access. Eight applications totalling 10.756MW were received; five applicants accepted their Connection Offer, resulting in a total accepted capacity of 8.545MW. This would treble the total renewable generation capacity on Shetland to over 12MW. Details of the new WTGs and their capabilities are provided in the following section.

G. Reactive Power Capability and Control

Section II introduced the potential for distributed generation to cause voltage rise. To mitigate against the impact on the network, SSEN introduced clauses within the Connection Offers which required distributed generation to provide continuous, automatic voltage control including a defined reactive power capability. In contrast, operating strategies that require a fixed power factor are fairly inflexible, with increased system losses due to the transportation of reactive power across the distribution and transmission network. Fig. 3 details the reactive power capability requirement.

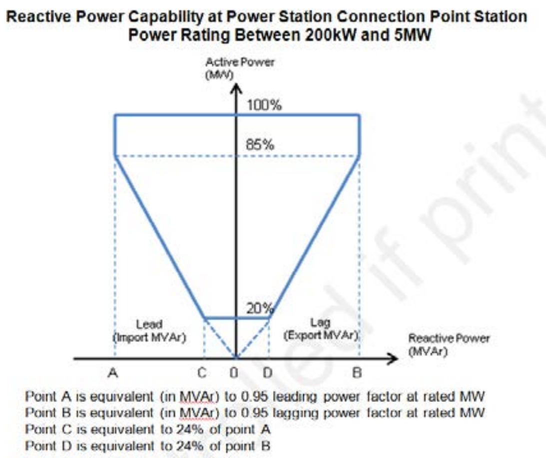

Figure 3. Reactive power capability at power station PoC (for power station rating between 200kW and 5MW)

Fig. 4 shows the voltage droop control requirement. The voltage control system shall be capable of working to a voltage setpoint between 95% and 105% of the nominal voltage. Unless otherwise stated in the Connection Offer, the initial voltage setpoint shall be 0.98pu where the connection voltage is 11kV or 0.99pu where the connection voltage is 33kV. For WPPs below 5MW, the slope characteristic of the voltage control system shall be adjustable over the range 2% to 8% with a resolution of 1%. Unless otherwise stated in the Connection Offer, the initial setting of the slope shall be 3% where the connection voltage is 11kV or 4% where the connection voltage is 33kV. For a step change in voltage at the PoC, the reactive power output response of the WPP shall be capable of achieving 90% of the required steady state change in reactive power in less than 2.5s. The settling time shall be less than 5s, with all oscillations being less than 5% of the new steady state value within this time.

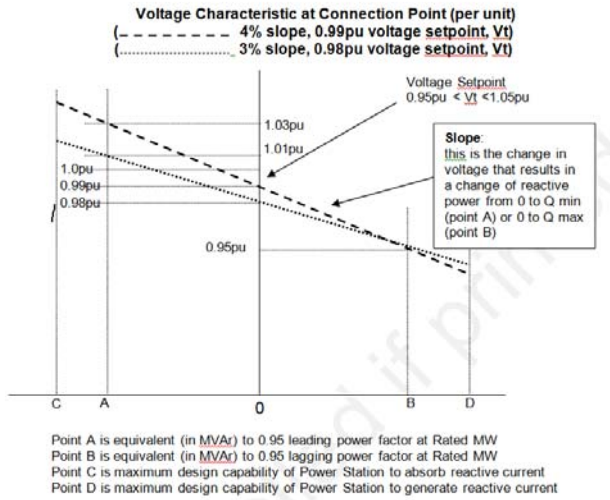

Figure 4. Requirement for voltage characteristic at the PoC

IV. Capabilities of Type IV Wind Power Plants

This section provides a high-level description of the electrical setup of typical type IV WTGs, their state-of-the-art electrical performance capabilities and several controllability and interfacing options at WPP level. This will serve as a basis for explaining the more detailed information on the electrical setup of the WPPs on Shetland provided in the following chapter.

A. Electrical Performance Characteristics of Type IV Wind Turbine Generators

Type IV WTGs employ a full-scale frequency converter, which enables full variable-speed operation and unlocks key grid integration features, such as flexible reactive power capability, a robust Fault Ride Through (FRT) performance and a wide voltage and frequency operating window. In this respect, the electrical generator is effectively decoupled from the grid [7]. One example of the type IV design is the ENERCON WTG, a high level single line diagram of which is shown in Fig. 5.

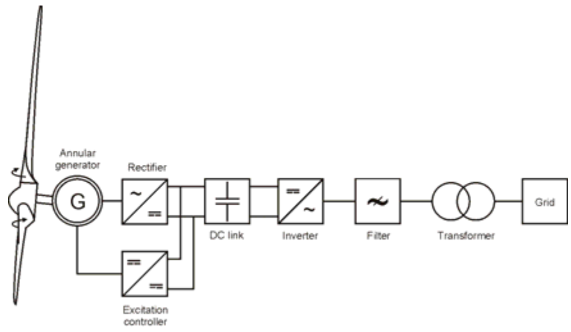

Figure 5. Typical type IV WTG configuration

The electrical generator is a multipole, field-excited annular generator, which can produce a variable-frequency AC output. This output flows sequentially through the rectifier, the DC link and the inverter modules. The inverter control system continuously measures the grid voltage vector at the 400V terminals of the WTG and sets the output current accordingly, and is thus the primary determinant of the WTG's electrical performance towards the grid.

Present type IV WTGs that have FACTS capabilities are in a position to contribute reactive power dynamically over a wide active power range, regardless of the prevailing wind conditions (i.e. without any active power output). Typically, ENERCON WTGs achieve a reactive power capability of ca. 0.5pu (based on WTG's nominal active power). A measurement of a typical P/Q diagram of an ENERCON WTG of the multi-MW class is given in Fig. 6.

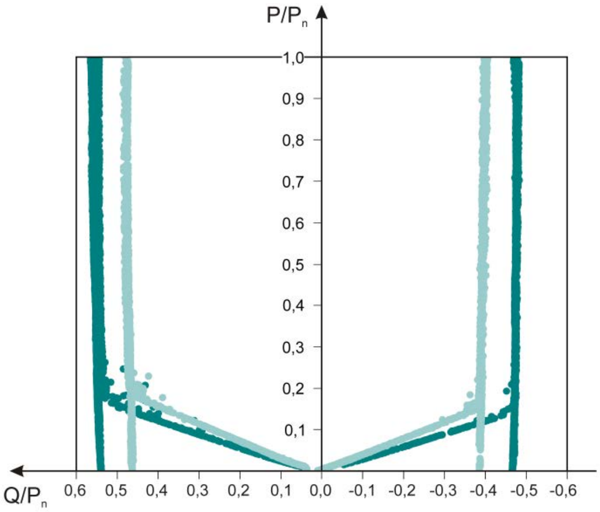

Figure 6. Typical reactive power capability of an ENERCON WTG

The area enclosed within the light green lines shows the WTG's possible active and reactive power operating points with the standard number of inverter modules, in comparison to the extended reactive power capability of the same WTG model with an expanded number of inverter modules, as shown in the area inside the dark green lines. Furthermore, both graphs show the capability to expand the reactive power operational area down to 0% of the nominal active power. With respect to the dynamic performance of the reactive power provision, a time constant (time required to reach 63% of the steady-state output after a setpoint change) in the order of 100ms can be achieved.

Regarding abnormal grid conditions, type IV WTGs can ride through large voltage disturbances on the grid and can modify their performance during the disturbance to support the grid voltage. ENERCON WTGs can ride through grid faults of any retained voltage for a duration of up to 5s per event, and provide active and reactive current during the fault in a flexible manner, via various customisable FRT modes. A rise time of < 30ms and a settling time of < 60ms can be achieved. Since 2016, an option to provide a negative sequence current component to help balance the voltage during an asymmetrical fault and prevent unintended tripping of protections [8] is available. Fig. 7 below shows the standard performance of the FRT mode that is used to meet the GB Grid Code.

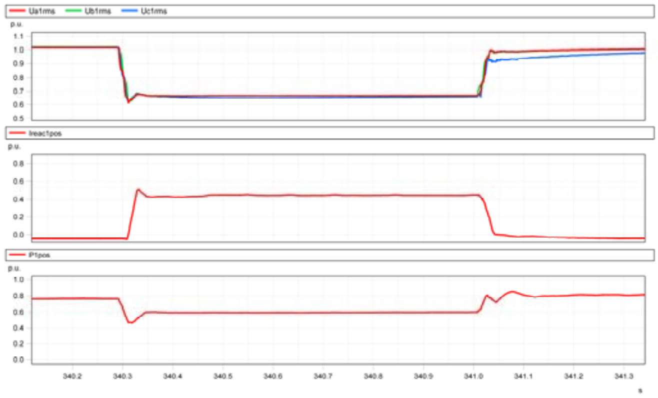

Figure 7. FRT performance of an ENERCON WTG

Similarly to the flexibility shown during abnormal voltage conditions, type IV WTGs have a wide frequency operating window and can also support the system during frequency disturbances. The frequency operating range for ENERCON WTGs is 43-57Hz, with the WTGs able to withstand a RoCoF of up to 4Hz/s. Beyond the more traditional primary frequency control feature that allows WTGs to continuously adjust the active power output depending on the system frequency, modern type IV WTGs are also capable of emulating the inherent inertial response of a synchronous generator. Without prior curtailment, the "Inertia Emulation" feature of ENERCON WTGs allows them to inject up to an additional 10% of the WTG's nominal active power, with a response time of between 500ms and 1s, and a duration of up to 10s [9], [10]. Fig. 8 shows a measurement of the performance of the Inertia Emulation feature.

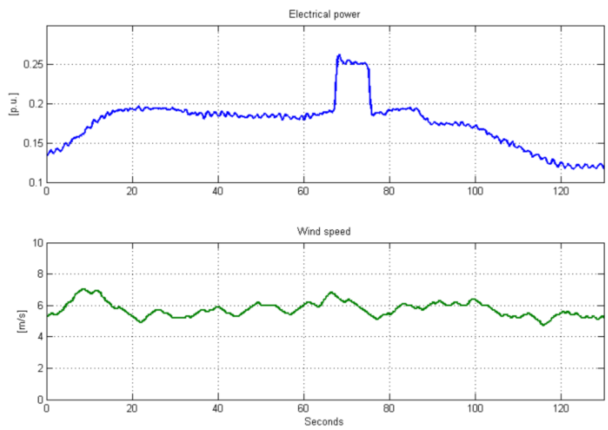

Figure 8. Performance of the Inertia Emulation feature at partial active power output

B. *Wind Power Plant Control and Interfacing Options*

The monitoring, control and interface requirements are normally tasks of a central control unit that takes measurements from measurement class Voltage and Current Transformers (VTs and CTs respectively) at the PoC and sends corresponding setpoints to the individual WTGs. Suiting different needs, two WPP controllers are currently available from ENERCON: the ENERCON Remote Terminal Unit – Control (RTU-C) and the ENERCON Farm Control Unit (FCU).

The ENERCON RTU-C is a more plug-and-play solution for small projects that communicates with the individual WTGs via the ENERCON SCADA Server. It does not require elaborate parametrisation through simulation studies, which comes however at the expense of a more standard response time. On the other hand, the ENERCON FCU communicates with the available WTGs through a dedicated high-speed optical fibre bus, allowing for much shorter rise- and settling times for reactive power and its associated parameters, a response that is determined mainly by the WTGs' inverters. Simulation studies are needed to properly parametrise the ENERCON FCU and often fine-tuning on site is needed. Both WPP controllers have a variety of controller modes available, including: voltage droop control, power factor control, reactive power control, active power limitation, and frequency-dependent active power control (only with the ENERCON FCU). Fig. 9 shows a typical control and communication topology.

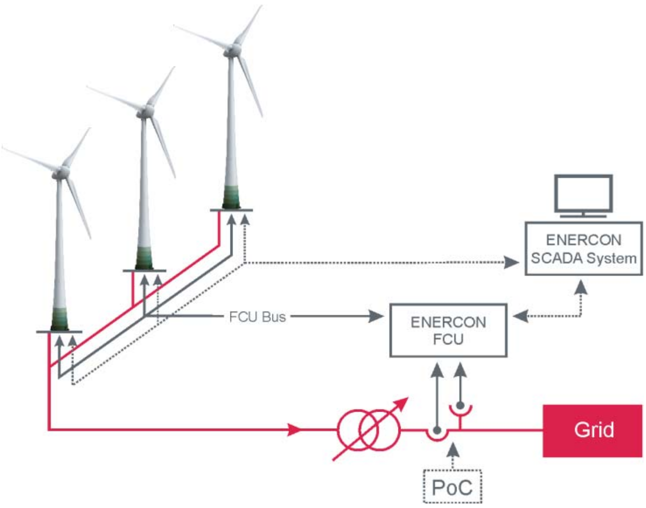

Figure 9. Typical WPP control and communication topology

External controllers can connect and send setpoints to both WPP controllers via a range of interfaces to suit different needs: MODBUS TCP, DNP3, IEC60870-5-104, analogue and digital contacts. Return signals are also provided. Depending on the selected interface, live measurements of grid parameters (voltage, current, active power, reactive power, etc.) can be also forwarded to the external controller, together with data accumulated by the ENERCON SCADA Server, e.g. power available, wind energy converter availability, current wind speed and direction, etc.

V. Shetland Operational Experience

Following the implementation of NINES, SSEN have been closely monitoring and adjusting system operation in order to optimise the performance of the power system on Shetland. Utilising project and operational experience, valuable findings are presented in this section.

A. Non-Synchronous Generation

On Shetland, there are three separate ENERCON WPPs with a total installed capacity of 8.4MW, which accounts for 68.5% of the total installed non-synchronous capacity and for 8.2% of the total installed generating capacity. All WPPs on Shetland have to comply with the GB Distribution Code and the project-specific Connection Offers issued by SSEN, and accepted by the WPPs' owners.

The first ENERCON WPP installed in 2014 consists of an E-44 WTG with a rating of 500kW and an extended reactive power capability of 630kVAr available from 20% of the nominal active power output. This WPP is further equipped with an ENERCON RTU-C that functions as the LCS and communicates to the LIC fulfilling the ANM requirements via analogue and digital contacts.

In 2016 an ENERCON E-82 E4 WTG, with a rating of 3MW was commissioned. The WTG's reactive power capability is extended to 2.3MVAr, available from 20% of the nominal active power output. This WPP is also equipped with an ENERCON RTU-C as the LCS and communicates with the LIC through analogue and digital contacts.

In 2017, a third ENERCON WPP consisting of five ENERCON E-44 WTGs, each with a rating of 900kW for a total installed capacity of 4.5MW, started exporting energy to the Shetland power system. All of the WTGs have an extended reactive power capability of 630kVAr available from 20% of the nominal active power output. To account for the greater capacity and the higher number of WTGs, this WPP is equipped with an ENERCON FCU as the LCS. Unlike the previous cases, communication to the LIC is now established through MODBUS TCP, a more flexible communication protocol that is easier to deploy and maintain.

All three WPPs operate in voltage droop control mode, as per the requirements presented in section III. Although not explicitly referred to in these requirements, closed-loop control was implemented, increasing the accuracy in the response delivered following an active power setpoint or a change in the voltage at the respective PoC.

Furthermore, the WTGs of all three WPPs are set up to ride through voltage events outwith their normal operational range but which would not trigger the protection elements parametrised as standard according to EREC G59/3. By reducing the occurrences of nuisance tripping, the WPPs can support the network for longer and more rapidly after the voltage event is cleared.

B. Wind Penetration

The annual wind penetration on Shetland (energy produced by wind as a percentage of the total electricity demand) throughout 2010 – 2018 is shown in Fig. 10.

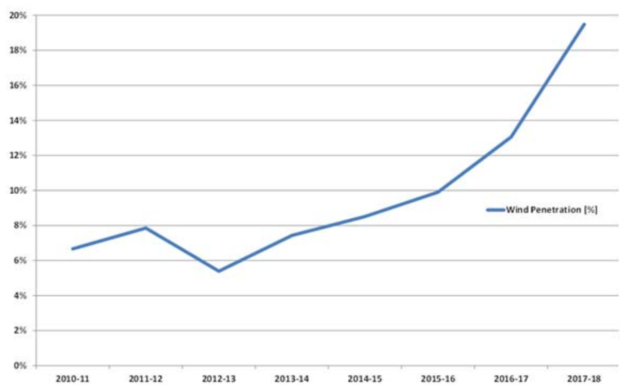

Figure 10. Annual wind penetration on Shetland (energy by wind generation as a percentage of total demand)

Between 2010–2014, the average annual wind penetration had plateaued at ca. 7% due to the limit of 4MW concerning firm renewable generation connections. Following the integration of flexible ANM connected generation, the wind penetration has risen year-on-year since

2014. The year of 2017 – 2018 represents the first full year of data with all generators from the NINES project connected. At the time of writing with six weeks of the financial year remaining, the annual wind penetration is currently 19.5%. The maximum instantaneous non-synchronous penetration recorded in 2017 was 57%. In comparison, according to the latest data available, wind generation (both onshore and offshore) accounted for 12.9% of the total electricity consumption in the UK during the first six months of the financial year 2017 – 2018 [11].

C. Resilience to Faults

Section II introduced the key protection requirements for WPPs in the UK, according to EREC G59/3, which are in use to protect both the generation and the network in the event of a grid fault. The need to have a closer look into these settings and possibly manage them differently in systems with high penetration of non-synchronous generation has been demonstrated in the isolated system of Shetland. Fig. 11 shows a minor event on one of Shetland's 29 11kV circuits, due to a secondary transformer fault at 08:53. The demand of the feeder is shown on the primary y axis (corresponding to the blue trace) and generation of that feeder on the secondary y axis (corresponding to the green and red traces).

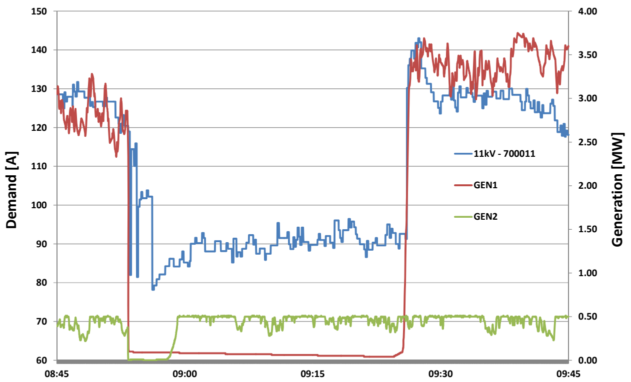

Figure 11. Protection operation due to minor network fault

It can be seen that this fault was enough to trigger frequency protection to Shetland's wind generation, despite the generation being connected to different circuits, at both 11kV and 33kV. SSEN contacted all generators connected to the Shetland system with a capacity greater than 50kW and asked them to modify their RoCoF setting from 0.125Hz/s to 1Hz/s. According to early indications, this has had a positive effect by preventing unnecessary trip events.

D. Active Power Response

The Shetland ANM collates generation data in real-time and uses them to determine a binding constraint value for the ANM connected generation. Generators are curtailed and released based on this constraint value, their queue position, and their current active power output. The example provided in Fig. 12 shows a WPP receiving multiple requests to adjust active power output and the associated response which is managed by the generator LCS. It can be seen that the WPP is adjusting fast its active power output in order to follow the commands of the LCS. The active power output follows closely what has been requested by the ANM, regardless of the frequency the setpoints change.

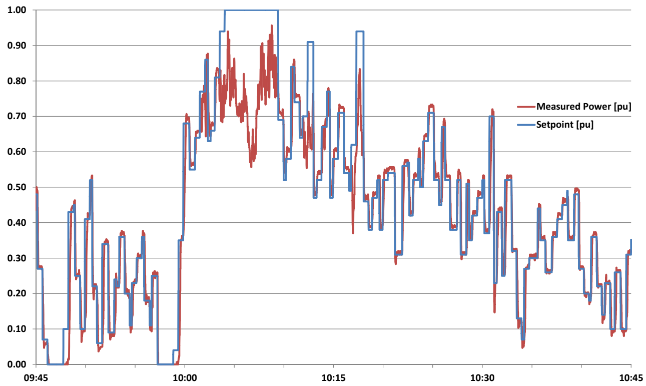

Figure 12. Response of a WPP to ANM active power setpoints

Any available capacity not used by a generator can be allocated to the next generator in the queue. This process is dynamic, but works exceptionally well as shown in Fig. 13.

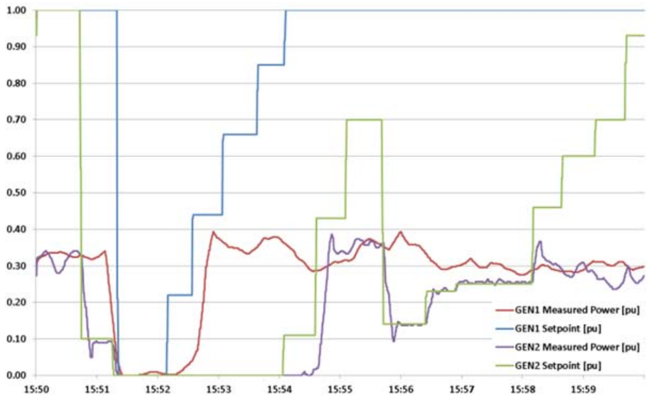

Figure 13. "Last in, first out" approach following curtailment

Fig. 13 shows generator 2 ("GEN2") curtailed first as per the "last in, first out" queue, followed by generator 1 ("GEN1"). The figure also shows that generator 1 is released first but does not take up the full setpoint due to the available wind, therefore the remaining available capacity is released to the next generator in the queue, generator 2.

E. Management of High Wind Speed Events

As introduced in section II, accommodating a significant penetration of wind generation during high wind speed events can be challenging. SSEN have managed this by using wind speed data provided by the LCS of generators and an ANM rule to minimise the rate of wind cut-out events.

Data, including the example introduced in Fig. 14, clearly show the WTG capable of continuing its operation and producing power even at 30m/s measured wind speed. After this point, the WTG's control system is averaging wind speed at much shorter timescales (12s as standard and 1s for gusts of +3m/s), meaning that despite the WTG still exporting power, larger changes in output might be experienced. This can become challenging for the operation of a small isolated system.

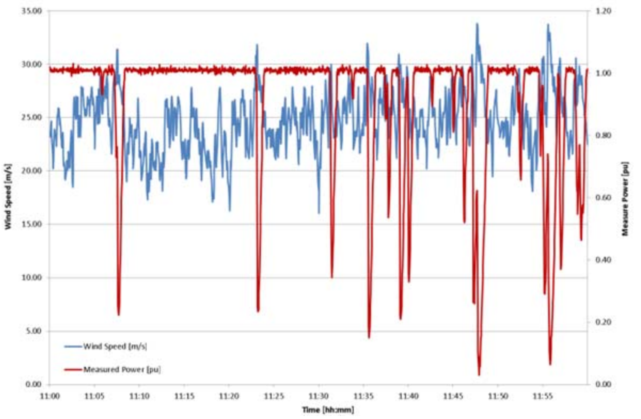

Figure 14. WTG active power output during a high wind speed event

The ANM system monitors the wind speed and is configured to issue a zero setpoint to the generator if a wind speed of 30m/s is recorded. Upon falling below the threshold of 30m/s a configurable timer is started. If the wind speed increases above 30m/s again prior to the timer reaching completion, then the timer would restart. Once the timer elapses the generator is placed back into service. In this way the number of cut-out events is significantly reduced as shown in Fig. 15.

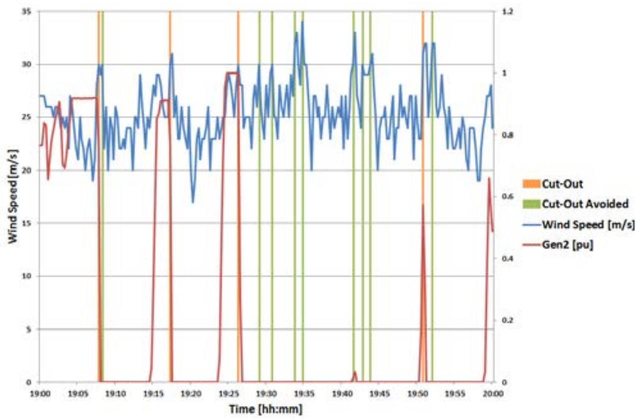

Figure 15. Evaluation of wind cut-out logic

In the one-hour period evaluated during storm conditions, the WPP would have recorded 13 cut-out events. With the cut-out logic enabled, these events were reduced to just 4 (shown in orange), therefore preventing 9 of cut-outs occurring (shown in green). This represents a significant reduction in large power swings experienced by both the WTGs and the conventional synchronous plant, and contributes to maintaining system stability with a high penetration of non-synchronous generation.

F. Performance of the Energy Storage

One of the historic BESS schedules and the corresponding impact on the demand on Shetland are shown in the following Fig. 16 and 17. The BESS was scheduled to discharge 3MWh at times of peak demand, reducing the conventional generation requirement. For instance, if the peak demand was 40MW, SSEN had to ensure there was 40MW of generation (plus suitable spinning reserve). By discharging the battery at 1MW during the peak demand, the conventional generation requirement was reduced to 39MW (minus the non-synchronous generation). A 75% round trip efficiency resulted in 4MWh of charging at times of low demand, when levels of curtailment were higher.

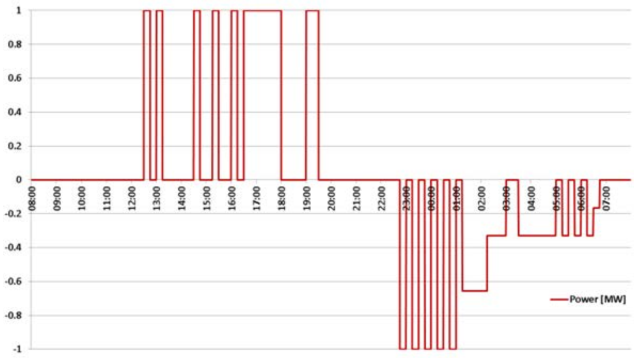

Figure 16. Battery schedule

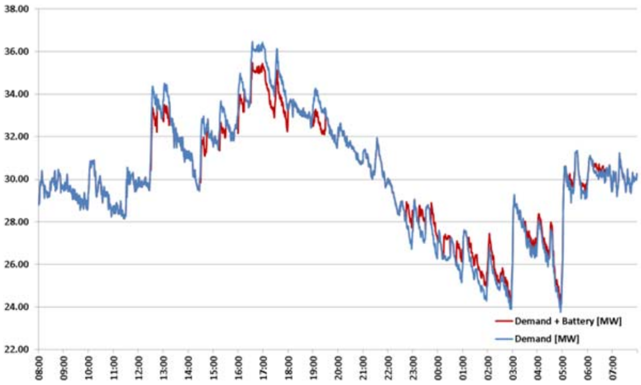

Figure 17. Impact of energy storage on the demand on Shetland

After a period of operation and evaluation, the knowledge and learning obtained were used by SSEN to develop a more intelligent form of control. This was in the form of an algorithm which would charge the BESS in direct response to generator curtailment. This algorithm was not actively trialled prior to the end of the project, although SSEN are currently looking at options to upgrade the BESS.

VI. Conclusions

State-of-the-art solar and wind generation come with a new set of characteristics with respect to their grid performance, a result of their use of power electronics to non-synchronously connect to the grid. The goal of decarbonising the energy system, when combined also with the changing patterns of demand (e.g. due to the electrification of transport), will pose new technical and operational challenges to the GB SO and DNOs. The nature and timescale of the different challenges with respect to the grid integration of non-synchronous generation will differ and depend on the specifics of the electrical system in question. However, it is valuable to draw on experiences gained in systems that already experience the conditions derived from the increased penetration of non-synchronous generation.

To this purpose, the isolated power system of Shetland, on track to generate 20% of the annual electricity demand by renewable generation, offers a first class case-study of how innovative systems can be designed to maximise the penetration level of renewable generation. This paper discussed the NINES project that trialled for the first time in the UK an ANM system capable of controlling generation and demand sources. Findings of this large scale and long term trial have been presented, covering the resilience to faults, the active power response by WPPs, the management of high wind speed events and the performance of energy storage.

Almost 70% of the total installed non-synchronous capacity is provided by 7 type IV ENERCON WTGs. The electrical performance characteristics that have been covered in this paper demonstrate that type IV WPPs are well suited to contribute to the stable operation of small, non-interconnected systems, by offering an additional degree of flexibility.

In November 2017 Ofgem announced that with some targeted investment, LPS would continue to run until at least 2025. This decision followed: an extension to emissions targets, issued by the EU Industrial Emissions Directive, for engines on isolated systems from 2020 to 2030, and permission for WPPs on remote islands, such as Shetland, to compete for a Contract for Difference (CfD) in the next auction for less established technologies, planned for 2019. There are several large WPP projects under development in Shetland that, if successful, would require an HVDC interconnector to the UK mainland and would see Shetland connected to the national grid of GB.

Prior to 2025, SSEN will continue to optimise system operation with the assets available, with a major upgrade to the Shetland ANM platform expected to be completed in Q2 2018 offering significant improvements to the human-machine interface and the flexibility of the system.

References

[1] European Environment Agency, “Europe's Onshore and Offshore Wind Energy Potential,” 2009.

[2] Department for Business, Energy and Industrial Strategy, “Digest of UK Energy Statistics,” 2017.

[3] F. Gonzalez-Longatt, E. Chikuni and E. Rashayi, “Effects of the Synthetic Inertia from Wind Power on the Total System Inertia after a Frequency Disturbance,” in *IEEE International Conference on Industrial Technology*, Cape Town, 2013.

[4] The Telegraph, “Balancing demand 'could cost National Grid £2bn’,” 17 June 2016. [Online]. Available: https://www.telegraph.co.uk/business/2016/06/26/balancing-demand-could-cost-national-grid-2bn/. [Accessed 08 March 2018].

[5] C. Masters, “Voltage Rise: The Big Issue when Connecting Embedded Generation to Long 11kV Overhead Lines,” *Power Engineering Journal*, vol. 16, no. 1, pp. 5-12, February 2002.

[6] Electricity Networks Association, *Engineering Recommendation G59 Issue 3 Amendment 3*, February 2018.

[7] T. Ackermann, Wind Power in Power Systems, 2nd Edition, Wiley, 2012.

[8] H. Emanuel, M. Schellschmidt, I. Mackensen and S. Adloff, “Asymmetrical Current Injection - Testing and Certification for New German Requirements,” in *15th Wind Integration Workshop*, Vienna, 2016.

[9] S. Engelken, A. Mendonca and M. Fischer, “Inertial Response with Improved Variable Recovery Behavior Provided by Type 4 Wind Turbines,” in *14th International Workshop on Large-Scale Integration of Wind Power into Power Systems*, Brussels, 2015.

[10] M. Fischer, S. Engelken, N. Mihov and A. Mendonca, “Operational Experience with Inertial Response Provided by Type IV Wind Turbines,” in *13th International Workshop on Large-Scale Integration of Wind Power into Power Systems*, Berlin, 2014.

[11] Department for Business, Energy and Industrial Strategy, *Energy Trends*, 2017.