Northern Isles New Energy Solutions: Active Network Management Stability Limits

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***Abstract*— The Northern Isles New Energy Solutions (NINES) project is addressing the current and future energy needs of the Shetland Isles by demonstrating the integration of low carbon energy sources using smart grid technology. In so doing, NINES will facilitate a major step towards a low carbon future for Shetland whilst leading and informing the wider international low carbon energy transition. The principal objective of the NINES project is to enable more renewable connections in a geographical area that is deemed to have the richest renewable energy resources in Europe. As such, the electrically islanded Shetland power network will see significant changes in operation as district heating schemes, domestic space and water heating systems, energy storage systems and new wind connections are developed, deployed and integrated under an active network management system. This paper discusses the role of inter-dependent system models in providing essential inputs to active network management (ANM) design and configuration. Early results from model development and testing are presented with specific focus on the stability limits for the connection of additional renewable generation when operating in conjunction with frequency responsive demand.**

***Index Terms*—Active Network Management, Demand Side Management, Distributed Generation, Dynamic Constraints, Smart Grid.**

I. Introduction

The Shetland Islands are situated in a region, 150 miles north of the Scottish mainland, where renewable energy resources are prevalent and are deemed to be the richest in Europe [1]. The geographic location and subsequent meteorological conditions around the northern isles not only brings vast quantities of renewable resource potential but also places restrictions and pressures on the existing network infrastructure. As the network is electrically islanded, stability issues [2] restrict distributed generation connections and pressure arises from the relatively high year-round heating demand [3]. The current connected capacity of renewable energy resource has reached the permitted upper limits that ensure system security and stability are preserved.

The Northern Isles New Energy Solutions (NINES) project aims to address technical [4] and commercial barriers associated with increasing renewable connections whilst maintaining the requisite levels of security [5] and stability. It is envisaged that the planning and deployment of smart grid technologies that provide greater control of renewable generation output and system load could substantially increase the renewable connection levels [6]. From a system management perspective this entails the research, development and deployment of an active network management (ANM) system that will monitor and control the network controllable devices such that operational constraints are avoided. In addition, the NINES project will directly inform the design of a replacement for the existing, ageing, Lerwick Power Station (LPS).

The NINES project is of sufficient scale that its focus on deploying and evaluating cost effective smart grid solutions will deliver valuable learning not only for the Shetland Isles but for the future UK and international smart grid transition. The ambitious nature of the project is reflected in the wide range of partners collaborating to deliver this smart grid demonstration project.

This paper presents an overview of the research and development of the envisaged modelling framework, the associated models and the tools that are required to inform the NINES project. Early results are presented and discussed from the dynamic modelling work package focussing on the stability rules format and parameters for the ANM system stability management algorithm which form inputs to the Unit Scheduling model.

II. The Shetland Network

The network on Shetland, Figure 1, is an electrically isolated system with a core 33 kV network and local distribution at 11 kV and low voltage. The 33 kV network is mostly overhead lines on land with subsea cables between the islands. Demand varies between 11 and 48 MW and is concentrated in the main town of Lerwick. Currently the power generation on the island is provided by three sources: Lerwick power station, Sullom Voe Oil Terminal and Burradale wind farm.

Lerwick Power Station has diesel generators with sufficient capacity to meet the total system load at peak but it is reaching the end of its life. The other main source of conventional generation is at Sullom Voe Oil Terminal (SVT). SVT

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generators are used to cover the internal demand of the oil terminal and to provide power to the Shetland network. The wind penetration on the network is approximately 7%. At present sudden changes in output from a 3.7 MW wind farm at Burradale can cause problems, particularly at times of low load or if SVT is not connected.

As an electrically islanded network, all variations in system demand must be met by these three generating stations.

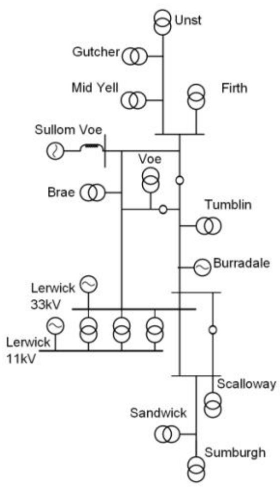

Figure 1 - 33kV Network Hub

III. Network Constraints and Barriers

Operation of this islanded network is subject not only to voltage, transient stability and thermal constraint issues, common to most networks, but also critical frequency constraints which limit the penetration of wind turbines. If the power exported from the wind turbines is lost due to a network fault, this can cause a significant generation-to-demand imbalance.

The wind resources on Shetland are excellent; in addition there are significant wave and tidal resources that could be exploited. However, exploitation of these resources is limited due to frequency stability concerns, as well as by voltage and thermal constraints. The NINES project objective is to overcome these constraints by the deployment of new technologies that will:

- Enable more renewable generating units to be connected
- Enable the management of demand to respect system constraints
- Test the use of energy storage technologies to enhance system operation
- Improve the operation of the existing Lerwick Power Station by optimising engine running and managing peak demand
- Contribute to the understanding required to construct the sustainable low carbon electricity networks of the future on other island systems, similar to Shetland, and also on mainland systems
- Demonstrate important technical and commercial learning for the global power industry

In overcoming the technical barriers to enable the objectives of the NINES project there is a positive consequence for the reduction of use and reliance of fossil fuels. In addition, new flexible connection arrangements and reward schemes for community participation will be identified and rolled out to ensure maximum benefits from the proposed system are realised by the system stakeholders and participants.

IV. Enabling Technologies for Active Network Management

Achieving the NINES objectives requires deployment of power system management technology to allow active management of generation, demand and energy storage devices. The project partners have identified the enabling elements and features of NINES:

- 1MW NaS battery installed at LPS (part funded by DECC) for energy balancing & potential frequency response
- Installation of 'smart' domestic space and water heaters for Domestic Demand Side Management (DDSM) and demand side frequency response into an initial 750 homes with options for a further 250.
- Augmentation of District Heating Network (DHN) boiler to enable increased wind power
- Connection of a 6-7MW wind farm operated in conjunction with the DHN
- Connection of small scale community renewables
- Introduction of commercial incentives to encourage consumer behavioural change and participation in the DDSM programme
- Deployment of an innovative Active Network Management (ANM) scheme to host control and automation functionality

The integration of smart grid technologies enables monitoring and control of the active network devices such that increased renewable generation can be connected without violating the network constraints.

V. System Management on Shetland

The management of the power system is currently achieved by manual control of conventional thermal generation to follow electrical demand with some responsive demand. The NINES project is testing an ANM based system operation on Shetland which will perform a number of automatic network management functions. These functions will be implemented using a number of separate algorithms deployed on hardware and software on the Shetland system. These algorithms will be able to operate independently or in collaboration. The system management functions are set out below.

A. System Balancing & Scheduling

The system balancing and scheduling algorithm coordinates and schedules the control of a range of controllable energy devices (NaS battery, domestic heaters, etc.). The application represents the various types of controlled devices in software and performs scheduling calculations to achieve the goals of the host network operator, including implementing principles of access or contractual commitments with different types of devices. In the NINES project, the objectives of the system balancing application will be to:

- Enable the transfer of energy according to agreed contracts and technical requirements
- Maximise the use of renewable generation
- Smooth the net demand profile to be met by conventional generation and thereby allow its operation to be improved
- Account for the operating characteristics and limitations of the controlled devices

The system balancing algorithm processes load and generation forecast data to support the creation of schedules for each of the controllable devices. Forecasts will be produced for different devices using a range of input data including historic records, values based on weather forecasts, and the expected operation of large loads. The scheduling function uses feedback data from a subset of controlled devices together with other power system information from to estimate the total available controllable demand, generation and storage (battery and thermal) and the degree of flexibility in their operation.

B. Transient Stability Management

The stability management algorithm will manage the frequency stability of the power system by setting the status, operating limits and frequency response characteristics of controlled devices. The stability management application will have access to the real-time status of all loads and generators and the aggregated frequency response available to the whole system.

The objective of the stability management algorithm is to ensure the power system does not enter operating states that are deemed unacceptable. An unacceptable condition is one in which the system would not survive all credible disturbances or one in which the network suffers unacceptable oscillatory stability. Credible disturbances include loss of generation and faults on overhead lines, cables, transformers or other network equipment.

C. Power Flow and Voltage Management

The real-time power flow and voltage management algorithms curtail loads and generators in response to thermal overloads and voltage constraints. The need for control requires the identification of constraint locations. These are locations on the network where it is possible for power flow or voltage to violate acceptable limits due to the operation of controlled devices. Prior analysis will identify the critical constraint locations, where managing power flow and voltage within limits at these locations will ensure limits are observed at all locations on the network.

VI. Power System Modelling Toolkit

Close co-ordination of control algorithms codified within the ANM system requires the steady state and dynamic characteristics of these new technologies to be fully understood. This requires the development of power system modelling which can assess the impact of the new energy and smart grid technologies on the network.

A critical component of the NINES deployment is the ability to model and forecast accurately all system states and dynamics to best utilise the characteristics of the controllable devices for network support and stability. The modelling work uses a framework of individual but inter-dependant models which together represent all relevant aspects of the Shetland system. The key components of this framework are described below.

A. Dynamic System Model

Fundamental power system dynamic models are required for the existing and newly connected devices to allow detailed analysis of the network under different modes of operation and network events. These detailed network models provide the foundation for the planning, scheduling and optimisation models required to plan and operate the system.

Furthermore, dynamic simulations will be conducted to identify the format of rules applicable for the ANM scheme and used to place limitations on the Unit Scheduling Model (Section IX.). In addition, specific parameters identified from the modelling and simulation work will be used to inform the design of the ANM scheme.

B. Customer Demand Forecast Model

This model provides the electrical and heating demand profiles for the network users. The demand profiles will be further categorised into flexible and inflexible demand groups. The inflexible group will offer the provision of determining the system base demand, at a node-by-node level, over the forecast period. The flexible demand component taken into consideration with the heat requirements of the users at each node will provide information of the level of demand response available for stability, peak lopping and valley filling functionality.

C. Unit Scheduling Model

This model receives inputs from the ‘customer demand forecast model’ and a ‘generating unit forecast model’ to schedule controllable energy devices to meet system objectives within the system constraints. This model is therefore central to understanding how the system should be operated. The proposed outcomes of this model include:

- Day ahead schedule for generation, energy storage, demand and Domestic Demand Side Management (DDSM) devices
- Generating unit power and energy curtailment forecasts
- System operational cost forecasts
- Available reserve and response requirements

D. System Development Optimisation Model

In order to evaluate how future network configurations perform and understand what the desirable configurations might be a system development optimisation model will be built. This system development model will utilise the unit scheduling model (or a simplification of it) to identify preferable or allowable system configurations taking into account the operation of low carbon generation, energy storage and the ANM system. The results will also give clear indications of how flexible the responsive demand, energy storage and non-firmly connected generation are required to be.

E. Strategic and Operational Risk Model

Complementary to the engineering modelling requirements, this risk model will identify the strategic and operational risks of developing a low carbon smart grid. Risk mitigation methods developed from the output of this model can be used by the network operator and stakeholders exposed to specific risks. Implementation of this model will be based upon ‘cause and effect’, ‘(non power system) system dynamic’ and ‘probabilistic’ approaches to quantify the associated risks and these modelling approaches are viewed as essential for a risk managed transition to a low carbon smart grid.

F. Economic and Commercial Model

The purpose of this model is to examine the economic impact of the system developments including energy affordability and carbon costs. The implications of the benefits associated with the cost of particular developments can be established within this model. The commercial aspect assesses the impact on system operation of different incentive and tariff structures and different access arrangements for different customer types and connected devices. The unit scheduling model can utilise the proposed commercial incentives and ancillary services opportunities to evaluate the impact on the power system. The commercial model identifies how to allocate efficiently to stakeholders the economic costs and benefits of the development of the low carbon smart grid.

VII. Use of the Modelling Toolkit for Configuration of the NINES Active Network Management Scheme

The Shetland ANM scheme is a deterministic, real-time system. The required responses and response times of an ANM scheme and the devices it controls to any given stimulus are determined during the design phase based on appropriate analysis and engineering judgement. The required response will depend on the power system requirements together with the mechanical and electrical capabilities of the controlled devices and measurement, control, and communications elements linked to the ANM scheme.

For the deployment of the Shetland ANM scheme the design will be informed and supported by the modelling work completed by a power system consultant (Parsons Brinkerhoff) and an academic research group (University of Strathclyde). The operational models will inform the configuration and influence the operational rules codified within the ANM scheme. The use of the outputs from each of the operational models is described below.

A. Dynamic System Model

The Dynamic System Model will identify the network constraints, which will limit the participation of new generators connecting to the Shetland Network. The development of the models and the simulation of the Shetland Network will produce results that indicate the maximum allowable wind connection for a given demand and conventional (and ‘firm’ connected) generation dispatch pattern.

The ANM scheme developer (Smarter Grid Solutions, SGS) will use the indicative results from the model to establish an upper limit on the allowable export (as a function of demand) from new renewable generators connected to the Shetland network. This export limit will be a conservative interpretation of results from the Dynamic System Model.

The ANM algorithms will ensure that this upper limit for generation export is respected in the production of the day-ahead energy schedules and in real time by modifying the targets or limits for power production or consumption of controlled devices. Controlled devices can be curtailed in real time to ensure that any export constraints are respected.

In addition to the export limits, the Dynamic System Model will inform the desired frequency response characteristics of the responsive demand. The frequency responsive characteristics of the new demand are enabled via a response curve defined by a deadband and a gradient.

B. Unit Scheduling Model

The Shetland ANM system calculates a 24-hour schedule for each ANM controlled device based on demand and generation forecasts and the availability of the ANM controlled devices whilst respecting:

- Device constraints
- Network constraints
- System Stability Rules
- Balancing & Scheduling Rules

In producing schedules for the controlled devices, the ANM system aims to maximise the amount of renewable energy connected to the Shetland network and reduce the variability of output from conventional generation whist ensuring the network remains safe and secure. The Unit Scheduling module allows the system designers to explore different applications of constraint rules. The Unit Scheduling Model outputs will be used to inform the design of the ANM scheme. In particular this model will inform the order in which constraints are satisfied.

C. Customer Demand Forecast Model

The ANM scheme scheduling calculations will seek to meet the energy requirements of controlled demand but manipulate the timing of when (electrical) energy is supplied to devices to enhance overall system operation. Thus, the scheduling calculations require forecasts of the energy required by controlled loads. This can take two forms:

- The total electrical energy to be delivered to a device (or group of devices) during a schedule period

- The profile of energy usage by customers, e.g. the draw of hot water or extraction of heat from storage heaters

The Customer Demand Model results will be used to establish profiles of energy usage for each of the devices connected to the ANM scheme. The energy usage profiles for use within the ANM scheme scheduling calculations will be evaluated by the ANM scheme developer.

VIII. Unit Scheduling Model

The scheduling engine is a key component of the ANM scheme. Its interaction with other elements of ANM operation is shown in Figure 2. A day-ahead schedule will be produced and passed to ANM devices. Real time monitoring and control systems will override the schedule if required to maintain network security. The real-time control systems also monitor deviations from the schedule and from the forecasts used and will trigger a re-schedule if required. On occasions, manual intervention may also over-ride a schedule.

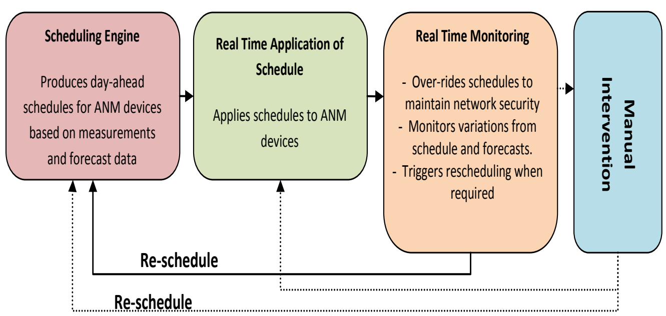

Figure 2 - The main processes that will be implemented in the ANM scheme

The design of the scheduling engine is being informed by research based on models for the solution of the Unit Commitment problem but this will be significantly different from traditional Unit-Commitment models. The ANM 'units' which are to be scheduled include: flexible demand, energy storage units and controllable renewable generation. There are a number of challenges inherent in producing a day-ahead schedule. These include the inter-temporal nature of the constraints and the requirement to use uncertain forecasts of both renewable generation and demand. In addition, since the network is electrically islanded, frequency stability is an important issues and the scheduling engine must maintain the network within the Dynamic Constraint Envelope (See section X.).

Beyond the fundamental scheduling issues raised by the project, the implementation of an ANM scheme draws attention to a range challenging issues that only crystallise when ANM systems are designed, built and implemented.

A. Key research challenges for ANM unit scheduling

Such a novel system poses interesting research orientated questions, answers to which are an important outcome of the scheduling model. This section gives more details of the key issues that are being considered:

- **The concept of unit scheduling:** unit scheduling for an ANM scheme will be significantly different from traditional unit-commitment models dealing with conventional generation units. The definition of 'unit' must be extended to include flexible demand, energy storage and controllable renewable generation (Generation that can be curtailed downwards). Previous work has incorporated wind generation together with Flexible Demand [7][8] and energy storage [9][10] into the unit commitment problem. One method is the use of Benders-decomposition, although work in this project is concentrating on the use of non-linear programming methods.
- **Inter-temporal constraints:** the use of flexible demand and energy storage leads to dependencies between time periods. For example, charging energy storage early in the day removes the ability to charge it later in the day. Scheduling flexible demand involves maintaining, the same total energy required over a 24-hour period whilst optimising *when* it is delivered.
- **Simple deterministic implementation:** a requirement of the project is that the ANM scheme uses straightforward deterministic algorithms running on real-time control platforms that allow the outcome and processing time of any set of events to be predictable in advance. The scheduling algorithm that will operate within the deployed ANM scheme will therefore not carry out 'optimisation' but will implement an algorithm based on simple control statements. A key area of research is the design and tuning of such an algorithm by using results from full optimisation based studies.
- **Forecasts data:** when producing a day-ahead schedule for energy devices there are a number of inputs that are forecast: renewable generation (mainly wind); fixed electrical demand; flexible demand requirements; and energy usage patterns. This introduces significant uncertainty into scheduling and the understanding, quantification and use of this uncertainty is a research challenge for the project [11][12].
- **Interaction with other systems:** The ANM scheme will not control the existing conventional generation on Shetland, the dispatch of these generating units remains with the network control room and not the autonomous ANM scheme. Operators dispatch the available convention generation based on a range of constraints and objectives, many which are based on engineering knowledge which cannot easily be codified in a fixed set of constraints or limits. This division of control means that the ANM scheme cannot know in advance how conventional generation will be dispatched. It is important that real dispatch patterns and decisions are understood and then the research will explore programming the ANM scheme to anticipate likely decisions and plan accordingly. As with forecast data this will lead to uncertainty and it is a research objective to understand how best to manage this.

It is important to note that the uncertainties introduced by the use of forecast data and the interaction with control room dispatch are uncertainties in producing useful schedules rather than uncertainties in final network security. As shown in Figure 2 real-time monitoring ensures that as the network state develops the ANM real-time monitoring and control functionality will over-ride any prevailing unit schedules, for example, forcing additional wind curtailment to maintain network security.

B. *Initial research outputs from ANM Unit Scheduling*

Initial work has focused on the design of scheduling models to address the challenges presented above. The problem is a multi-period optimisation involving a range of energy devices which can be scheduled within specified limits. As the dispatch of conventional generation is not included, the problem can be defined without the need for integer or binary variables and a non-linear programming approach is being developed that extends existing work on linear and heuristic optimisation of energy storage devices [13][14]. The objective of the optimisation is primarily to minimise the curtailment of renewable generation and secondarily to smooth the total conventional generation schedule with the following attributes:

- Inputs forecasts of renewable generation and can curtail output when required
- Inputs forecasts of flexible and inflexible demand
- Resolves inter-temporal constraints associated with energy storage and flexible demand.
- Resolves network power-flow constraints
- Inputs 'Dynamic constraints' [15]
- Outputs schedules for energy storage, flexible demand, expected renewable generation and expected generation curtailment.
- Outputs schedules for total conventional generation requirements.

The scheduling model is currently being tested.

IX. Dynamic System Models

A. *Frequency-Responsive Demand*

Frequency sensitivity of both domestic heaters (space and water heating) used in DDSM and a district-heating boiler is based on a local built-in measurement of frequency and locally controlled demand. The active power is driven either up or down as actual conditions dictate.

A user-defined load model was developed combining representation of both DDSM and boiler frequency responsive demand. The following specific features were included in the user model through associated parameters:

- The droop characteristic specified in MW/Hz per single customer.
- Frequency dead-band setting is provided in mHz.
- Demand variations are limited between specified maximum and minimum values per single customer.
- Number of single customers lumped within selected load.
- The rate of ramp of load variation in MW/sec.

B. *NaS Battery*

The software holds a dynamic model of a battery (CBEST model in the PSS/E library), with voltage and reactive power control. The model replicates actual reactive current restrictions for the NaS battery.

A user model (FRQBAT in the PSS/E library) was developed to represent frequency responses of the NaS battery using a supplementary frequency-sensitive signal.

The control logic incorporates a proportional droop-based response. Additionally, instantaneously changing the battery output to the upper or lower limits can be forced through this model during simulation time (either manually or by using additional models such as event-driven response). When the output is forced up to its limits, any droop-based response will be cancelled.

Furthermore, the FRQBAT model does not support any proportional-integral control as it is performed in the minute timeframe and is governed by secondary rather than primary frequency control.

Coordination between FRQBAT and CBEST models is illustrated in Figure 3.

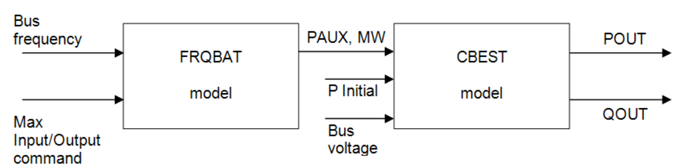

Figure 3 - Coordination of FRQBAT and CBEST models

C. *New Wind Farms*

The type of turbine that was considered for the modelling is an induction generator connected to the grid through full converter output. Power conversion is based on a converter system which decouples the generator from the grid.

Usage of a specific model was not available from the manufacturer at the current stage of the project. Therefore, a generic wind turbine model can be used (e.g. WT4G1 Wind generator model with power converter (Type 4) model available within the standard PSS/E library).

D. *Micro Wind Turbines*

It is expected that a significant number of small and micro wind turbines will be connected to the Shetland grid, ranging in size from 5 to 100 kW. The background generation technologies vary between permanent magnet alternators connected via rectifier (inverter) and induction machines with direct AC grid connection.

The Type 4 generic wind turbine model in PSS/E is a suitable modelling choice for either permanent magnet or synchronous generators connected via inverters; however, the voltage control range could be reduced or even cancelled in this case.

Induction generators can be modelled using either the CIMTR3 model or the generic wind model of Type 1 in PSS/E. The Type1 wind model is a more detailed industry developed generic one simulating the performance of a wind turbine employing a conventional induction generator directly connected to the grid.

Engineering Recommendation G83/1 [16] outlines a typical set of protection for small embedded generation and ranges of settings.

E. Burradale Wind Farm

The existing Burradale wind farm utilises three directly connected induction generators and two double-fed induction generators (DFIG) with total installed capacity of 3.68 MW [17].

The generic Type 2 wind generation model in PSS/E represents induction generators with variable rotor resistance control. Generic dynamic models for DFIG technology can be used from the PSS/E library, namely Type 3 models.

F. Lerwick Power Station

Lerwick power station is based on diesel generation distributed between Station A and Station B (Figure 1). Diesel generators operated with other synchronous machines can be modelled using the DEGOV1 Woodward diesel governor model of PSS/E. The ESAC5A model represents the excitation system supplied from the brushless rotary exciter.

The generation units are equipped with the under- / over-frequency and voltage protection.

For verification purposes an actual grid event was modelled. The simulation results reproduced the actual frequency traces for the event using the DEGOV1 model of diesel generation.

X. System Dynamic Modelling

The purpose of the dynamic simulations is to identify the format of the stability rules and evaluate and determine the parameters of these rules [18][19][19]. The purpose of this is to place limitations on the Unit Scheduling Model and provide operating rules for the ANM scheme to ensure system stability. The evaluation process seeks to determine the maximum level of wind penetration for the conventional generation dispatch patterns at different levels of system demand. In addition, the inclusion of increments of DDSM heating elements will be investigated along with the battery system [21] to identify the impact that they have on the stability rules and the subsequent increase in permissible wind generation.

Offline dynamic simulations using PSS/E and the dynamic models described in the previous section, were conducted to determine the maximum permissible connection of wind generation for cases ranging from minimum to maximum system demand. The dynamic simulations return results that indicate the system response when securing the system against loss of wind generation. Levels of wind penetration are identified that when tripped from the network maintains system frequency within limits (+/- 2Hz in the case of the Shetland system)

The level of permissible wind, P^{Max}_{wind}, allowed on to the system is a function of the dispatched conventional generation (CG) and the available frequency responsive devices (i.e. DDSM and NaS Battery) as defined in (1) below:

$$p_{Wind}^{Max} = f_1(CG) + f_2(Battery) + f_3(DDSM) \qquad (1)$$

Where the functions, $f_1(CG)$, $f_2(Battery)$ and $f_3(DDSM)$ determine the system inertia and response parameters for each of the connected devices. The above formulation can be augmented to include variables that represent the dispatched units and available units for frequency response.

$$p_{Wind}^{Max} = f_1(a_1CG) + f_2(a_2Battery) + f_3(a_3DDSM) \qquad (2)$$

where,

$$f_1(a_1CG) = a(CG_{unit_1}) + b(CG_{unit_2}) \ldots + \ldots n(CG_{unit_n}) \qquad (3)$$

$$f_2(a_2Battery) = c(Battery) \qquad (4)$$

$$f_3(a_3DDSM) = d(DDSM_{Group_1}) + e(DDSM_{Group_2}) \ldots + \ldots m(DDSM_{Group_m}) \qquad (5)$$

where *a, b, n, c, d, e, f & m* are binary coefficients to represent online machines/components.

The results of the analysis of the envelope of the set of conditions that maintain the system within permissible frequency limits resulting from a system disturbance, in the form of loss of wind generation, is illustrated in Figure 4. The levels of maximum permissible wind generation can be gauged from the vertical axis depending on the actual conventional generator dispatch pattern for different system demands. For minimum demand it can be seen that there are three potential levels of wind allowed access to the network for the three different conventional generation dispatches. Taking a linear approximation under the simulation results ensures that conservative stability limits are used in the Unit Scheduling Model and the ANM scheme. As depicted in Figure 4 operating margins (OM1 & OM2) can be further introduced to ensure that conservative stability limits are in place for all cases.

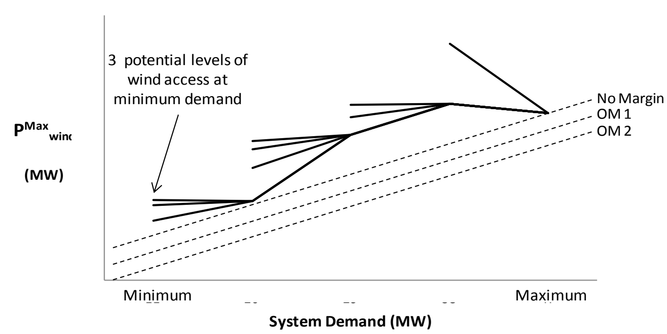

Figure 4 - Illustration of Conventional Generation Dispatches and Levels of P^{Max}_{wind} Connections that Determine Stability Rules

Subsequent dynamic simulations that include increasing levels of DDSM (as DDSM comes online in the Shetland system) and the NaS energy storage device will yield the relationships for the various system demand levels as illustrated in Figure 4. The conservative linear relationship can be extracted and combined to form the frequency stability rules for different system combinations and load variations to identify the levels of renewable generation access to the network. This is illustrated in Figure 5. For example, at minimum demand the level of wind penetration can be identified for scenarios that involve the operation of the conventional generation, the availability of different quantities of DDSM and whether the NaS energy storage unit is online. The limits described by Figure 5 define the dynamic envelope.

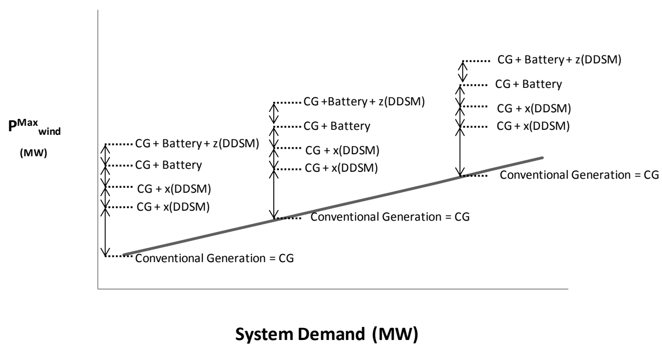

Figure 5 - Illustration of Stability Rules for Conventional Generation Dispatches Combined with Frequency Responsive Devices

XI. Conclusion

The paper has presented a description of the modelling techniques required to inform and implement an ANM scheme in an electrically islanded distribution network along with an overview of the system components. The additional complexity and risk inherent in a transition to a smart grid approach to system operation requires substantial simulation effort and the development of new models to fully examine the operation of new power system configurations. The main features of the Unit Scheduling and Dynamic System Models have been set out. The use of the results from these models for ANM system configuration has been discussed. The dynamic analysis presented gives an indicative and reconfigurable rule format for the Unit Scheduling model for day-ahead scheduling and the conservative real-time stability boundary for the system operation which will be implemented by the ANM system. The proposed Unit Scheduling model adapts the unit commitment problem to include new connected controllable devices and incorporate new systems constraints (frequency stability).

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