Scottish & Southern Electricity Networks

University of Strathclyde Engineering

NINES

3A Frequency Response: Commercial Impact Report

Prepared by

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List of acronyms

ACG	Active Network Management Controlled Generation
ANM	Active Network Management
BESS	Battery Energy Storage System
BUR	Burradale
DB	Dead-band
DFIG	Double-fed induction generator
DSM	Demand Side Management
FR-DSM	Frequency responsive demand side management
LPS	Lerwick Power Station
NINES	Northern Isles New Energy Solutions
SSEN	Scottish and Southern Electricity Networks
SVT	Sullom Voe Terminal
UoS	University of Strathclyde

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Project Background

In 2010, a licence obligation was put in place requiring Scottish and Southern Electricity Networks (SSEN) to present an Integrated Plan to manage supply and demand on Shetland. The Shetland Islands are not connected to the main GB electricity network and, as such, face unique electrical challenges – but also a unique opportunity to decarbonise supply. Under the licence condition, this Integrated Plan was required to demonstrate that it had identified a solution based on the lowest lifecycle costs, taking into account its environmental obligations.

As part of the Integrated Plan submission, consideration was given to: the upgrading or replacement of Lerwick Power Station, the impact of third party generation requirements, the abundance of renewable energy resources, and the future demand on Shetland. The factors influencing the supply and demand issues on Shetland necessitated an innovative approach to their management. However, with innovation comes the need to trial solutions. As a result, SSEN originally proposed to split the implementation of the Integrated Plan into two phases:

Phase 1 (Northern Isles New Energy Solutions 'NINES') – implementation of the infrastructure necessary to actively manage demand, generation, reactive compensation and energy storage assets. These elements were coordinated to maximise the amount of energy harvested from renewable generation while maintaining supply quality and security. In doing so, two principal effects are achieved:

- a reduction in maximum demand; and
- a reduction in the electricity units generated by fossil fuels

Phase 2 (Shetland Repowering) – upgrading or replacement of Lerwick Power Station taking into account the learning acquired during Phase 1 and, where appropriate, extending the Phase 1 technology.

NINES Elements

NINES was designed and developed to operate in conjunction with Lerwick Power Station with the main aim of informing the optimum repowering solution. Whilst its primary objective was to trial 'smart grid' initiatives, importantly NINES has delivered funded elements and infrastructure that are expected to endure as part of, or alongside, the Shetland new energy solution. Central to the project has been the creation of an integrated set of models designed to anticipate the impact of NINES, covering the following themes:

- Dynamic stability model
- Steady state model
- Unit scheduling model
- Customer demand forecast model
- System development optimisation model
- Strategic risk and operational risk model
- Shetland economic model
- Commercial model

The aims of NINES have been to increase understanding of:

1. How best to accommodate Shetland's significant wind potential on a small distribution network; and
2. How the existing and known future demand on the island can be securely managed on a constrained, isolated system.

These models predict the behaviour of the energy systems on Shetland, and served to validate each of the key elements of NINES as they were added. Following this validation process, these models have been used to inform the development of the New Energy Solution realised through the competitive process. Through the successful operation of NINES, the infrastructure and knowledge to reduce the peak capacity requirement for any replacement solution to a level dependent on the particular assets connected, and the characteristics of the new solution have been determined. The NINES project assets are described below.

1. 1MW, 3MWh BESS at Lerwick Power Station
A 1MW, 3MWh battery acts as an energy storage system on the Shetland Network. In addition to facilitating the connection of new renewables, the battery assists in the operation of the existing island network by helping to reduce conventional generations' contribution to meeting peak demand. The battery has helped to accommodate the connection of new renewable generation that would otherwise not have been able to connect.

2. Domestic demand side management with frequency response
As part of the wider NINES benefits, Hjaltland Housing Association contracted with Glen Dimplex to install advanced storage heating and water heating in 234 existing homes. These new storage and water heaters were provided through Hjaltland and ERDF funding and have been specifically designed to use a much more flexible electrical charging arrangement. This new charging arrangement is determined based upon the predicted demand, weather forecasts, availability of renewables and other network constraints. This initial roll out was intended to help gauge the effectiveness of storage and demand side response at the domestic level.

The heaters incorporate additional insulation to minimise heat loss and are fitted with programmable timers and an integrated fan to allow users much better control of temperature and operating times compared to conventional storage and water heating systems. The new heating system is designed to be more efficient, while giving the customer full control of both temperature and operating time whilst allowing for charging at times that best suit the network.

Glen Dimplex developed the storage and water heaters to provide frequency response based on requirements issued by SSEN. The devices are capable of shedding load in response to a loss of generation in 350ms.

3. Renewable generation
Shetland has some of the richest renewable energy resources in Europe and there is significant interest on the islands to connect a range of new renewable generators. There is a mix of wind and tidal generators currently connected that range in scale from 45kW up to 4.5MW. Prior to NINES these generators could not connect to the network due to the underlying voltage and stability constraints. Connecting more renewable generation, which is unavoidably intermittent, would have exacerbated these problems.

To address this, NINES has trialled an active network management system which has offered renewable connections to developers. In return, they are required to consent to being constrained when the system cannot accommodate their generation. The measures that have been developed and trialled under NINES are reducing this constraint by being able to actively provide demand when there is renewable resource available.

These arrangements would be necessary even if Shetland is to become electrically connected to the National Grid at some point in the future. Current SSEN ANM systems in Orkney and the Isle of Wight evaluate real-time thermal constraints of the cable to calculate a limit on ACG export. Furthermore if a single mainland link is damaged, this could result in a prolonged outage, which would mean that Shetland would once again be electrically islanded.

4. Active Network Management (ANM) system
The ANM system calculates constraint limits and uses the binding constraint to provide appropriate set points to ACG. At present a day ahead scheduling model uses forecast information and aggregated daily energy requirements to schedule controllable demand. By establishing controllable demand on the island progress has been made in exploiting and maximising Shetland's wind generation potential on an islanded basis, and in reducing the generated output from thermal generation.

A key driver for the trial has been to develop an understanding how these technologies work and interact in a real-life environment.

The following report is one of a number of related reports undertaken by the University of Strathclyde and focuses on domestic demand side management with frequency response.

NINES UoS Reports	
1A	DSM: Customer Impact
1B	DSM: Infrastructure
1C	DSM: Network Benefits
2A	Battery: Operational Effectiveness
3A	Frequency Response: Customer Impact
3B	Frequency Response: Operational Effectiveness
4A	ANM: Operational Effectiveness
4B	ANM: Functional Design Report
6A	Commercial Arrangements and Economics Report
7A	UoS Knowledge & Learning Report

Table 1 NINES UoS learning reports

The main objective of this report is to provide an understanding on how Frequency Responsive Demand-Side Management (FR-DSM) can contribute to the secure operation of the Shetland's network with high penetration of wind generation by answering the following questions:

- For each FR-DSM (storage asset) what would be the equivalent size of diesel machine required to provide the same response?
- Provide examples where the operation of the system has resulted in positive or negative effects on stability.

In order to answer the above questions, the dynamic model of the Shetland's network used in the previous phase of NINES has been updated to include a new FR-DSM dynamic model as made available by Scottish and Southern Electricity Networks (SSEN). The frequency performance assessment has been centred on observing the frequency nadir under different disturbances and operational conditions.

Shetland Network

The islanded distribution network in Shetland consists of 11-kV and 33-kV circuits which supply power to a population of 23,000 people. Figure 1 shows the single line diagram of the 33-kV network in Shetland including the location of primary substations and generation sources.

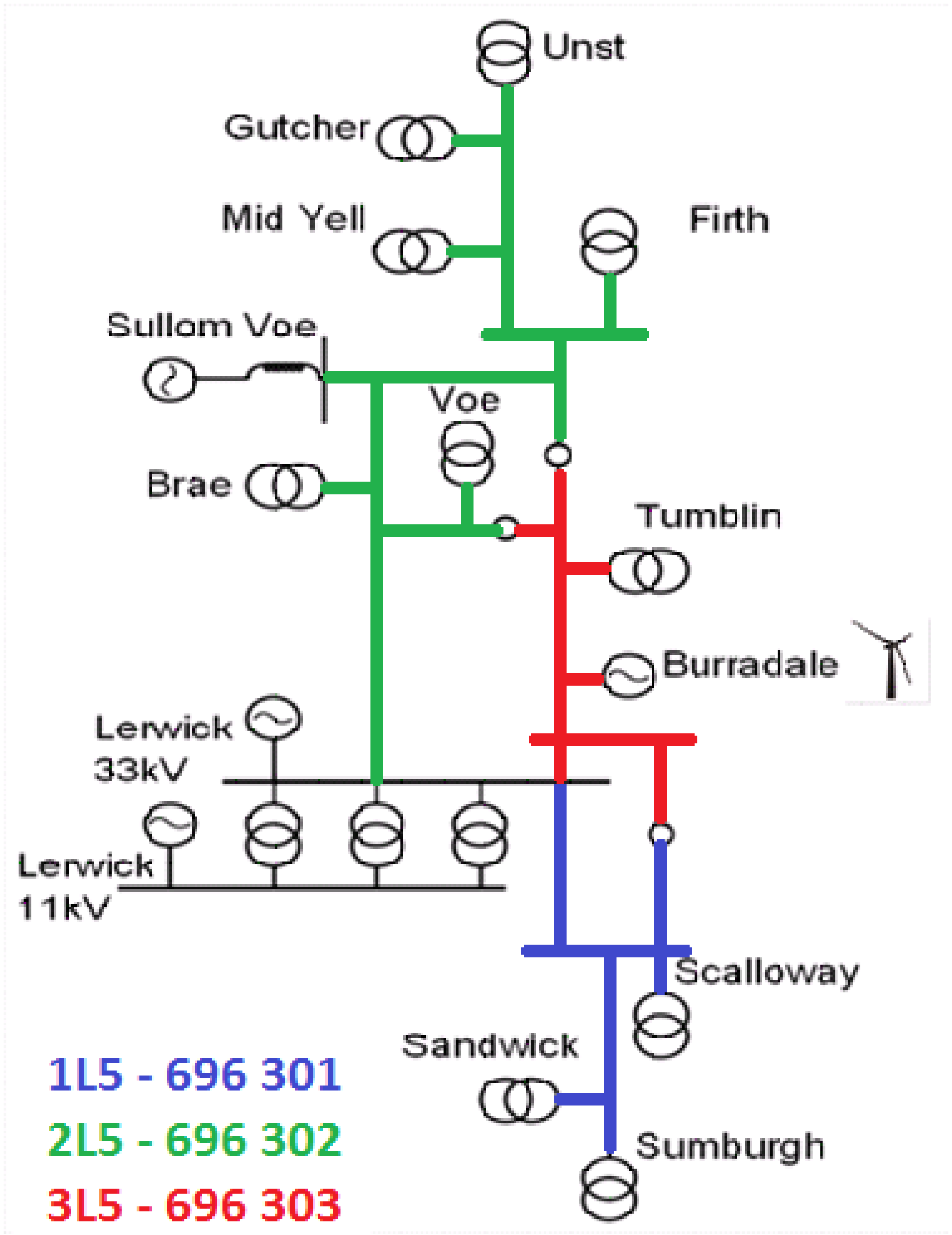

Figure 1 Schematic representation of the 33kV Shetland network prior to NINES including the location of primary substations and generation sources

The system demand varies between 11 and 48 MW and is concentrated in the main town of Lerwick. The minimum, average and peak demands recorded in 2015 were: 13.05 MW, 29.47 MW and 46.77 MW, respectively. This system demand is supplied by three power stations located at three locations: Lerwick Power Station (LPS), Sullom Voe Terminal (SVT) and Burradale Wind Farm (BUR). LPS currently consists of a number of diesel generators and gas turbines as detailed in Table 1 with sufficient capacity to meet the total peak system demand.

Unit Number	Station	Engine Type	Rated Output (MW)
3	A	Diesel Engine	4.6
4	A	Diesel Engine	4.6
5	A	Diesel Engine	4.6
8	A	Diesel Engine	3.5
10	A	Diesel Engine	4.6
11	A	Diesel Engine	4.6
13	A	Diesel Fuelled Gas Turbine	5
14	A	Diesel Fuelled Gas Turbine	5
21	B	Waste-Heat Steam Turbine	2.1
22	B	Diesel Engine	8.1
23	B	Diesel Engine	8.1
24	B	Diesel Engine	12.7

Table 1 LPS diesel generators and gas turbines.

The other main source of conventional generation is at SVT. SVT generators are used to supply the internal demand of the oil terminal and to export power to the Shetland network. SVT has up to two gas turbines connected in parallel with the system, each with a rating of 20 MW. BUR with an installed capacity of 3.68 MW consists of five double-fed induction generator (DFIG) wind turbines. BUR is connected under a firm connection agreement and typically operates at 52% annual capacity factor due to the excellent wind resource on Shetland[1].

[1] Shetland Aerogenerators. Burradale Wind Farm. Available: http://www.burradale.co.uk/

Study scenarios and assumptions

Frequency performance assessment has been conducted using both, scenarios created by UoS (based on assumptions and engineered data), and actual measured data made available by SSEN. Study scenarios were defined considering different network demand levels and availability of FR-DSM.

1. Events consider losing all wind generation (i.e. the existing Burradale wind farm but also future connections) for the following demand levels in 2015:

- Minimum demand (13.05 MW)
  - SVT units 1 and 2 are online and exporting around 5 MW
  - LPS units 8 and 22 are online
  - Battery is fully charging
  - Burradale wind farm output around 3.68 MW

- Average demand (29.47 MW)
  - SVT units 1 and 2 are online and exporting around 10 MW
  - LPS units 21, 22 and 23 are online
  - Battery is on standby
  - Burradale wind farm output around 3.68 MW

- Maximum demand (46.77 MW)
  - SVT units 1 and 2 are online and exporting around 15 MW
  - LPS units 11, 21, 22, 23, and 24 are online
  - Battery is delivering 1 MW
  - Burradale wind farm output around 3.68 MW

2. The equivalent size of diesel machine required is investigated for each demand level when SVT is offline as the network frequency is strongly determined by the SVT units when they are online.

3. Two main disturbances have been analysed in this report:

- Line 2L5 trip - line 2L5 describes the cable between LPS and SVT

- SVT unit trip.

Key Points

- The equivalent size of a diesel generator required to provide the same response to FR-DSM highly depends on the system inertia. The amount of FR-DSM required to provide a similar response to one of the existing diesel machines at LPS increases as the total system inertia decreases. Moreover, a diesel machine provides a better frequency response as the rate-of-change-of-frequency decreases leading to improved system stability.

- Some severe network disturbances result in large frequency deviations outside the statutory limits. However, FR-DSM could be used to prevent the network frequency from falling below the permissible limits. As expected, the effectiveness of using FR-DSM depends considerably on its availability.

1

For each FR-DSM asset what would be the equivalent size of diesel machine required to provide the same response?

1. For each FR-DSM asset what would be the equivalent size of diesel machine required to provide the same response?

The response of FR-DSM to a frequency variation is the opposite to that of a generator. In the case of a drop in frequency, a generator provides more power while frequency responsive demand needs to decrease its load.

When the system frequency starts to decline, the frequency dynamics of the system are dominated by the inertial response of the on-line synchronous generators and the system frequency drop will decrease at a rate mainly determined by the total inertia. Synchronous machines inherently contribute some of their stored inertial energy to the grid, reducing the initial rate of frequency drop. The smaller the system inertia, the faster the system frequency will decrease. Moreover, the inertial frequency response also includes some portion of the generator governor response trying to arrest the frequency decay.

1.1 FR-DSM equivalent to 4.6 MW diesel machine

FR-DSM can provide a similar performance to that of a diesel machine when it is equipped with appropriate droop characteristics, expressed in terms of percentage of rated power change per Hz. To estimate the amount of FR-DSM required to provide a similar response to one of the existing diesel machines at LPS, the following methodology has been applied:

1. A diesel engine with a rating of 4.6 MW (G05) is connected at LPS.
2. The engine is operating at (0.65 pu).
3. FR-DSM is not used.
4. Run the simulation for 1s without any disturbance.
5. Apply a disturbance at 1s which is the loss of maximum permissible wind generation for minimum and maximum demand levels (3.58 MW for minimum demand and 7.94 MW for maximum demand).
6. Observe system frequency.
7. Disconnect the diesel engine and repeat the previous steps 4 and 5 with FR-DSM active.
8. Gradually increase FR-DSM until a similar frequency behaviour to 6 is observed.
9. The FR-DSM amount obtained is equivalent to the existing 4.6 MW diesel engine that provides the same response.

For maximum demand: LPS units (3, 4, 5, 8, 10, 22, 23, and 24), 7.94 MW of wind and the Battery + 1 MW.

For minimum demand: LPS units (5, 8 and 22), 3.58 MW of wind and the battery - 1 MW.

Figure 2 shows the system frequency response when a 4.6 MW diesel generator running at 3MW with 1.6MW spinning reserve (red line) and equivalent FR-DSM (black line) are used during maximum demand. At 1s, 7.94 MW of wind generation is switched off causing the system frequency to drop to 49.3 Hz with a rate-of-change of frequency of 1.03 Hz/s in the case of the diesel generator (red line). To get a similar frequency response about 1.637 MW of FR-DSM with the current dead-band (0.3Hz) and droop characteristic (500% / Hz) is connected to the system. However, the rate-of-change of frequency is slightly higher in this case (1.08Hz/s) as the system inertia is slightly reduced when the 4.6 MW of diesel machine is replaced by the equivalent FR-DSM.

As described in NINES 1A DSM Customer Impact Report, 1B DSM Infrastructure Report and 1C Network Benefits Report, the number of homes currently on Shetland equipped with FR-DSM devices is 223 with an average value of 7.19 kW for each home. The total installed power of FR-DSM is therefore about 1.639 MW, which is equivalent to approx. 3.5% of the maximum demand. When the devices in the 223 homes are fully charging, theoretically they can provide a similar frequency response to an existing 4.6-MW diesel machine at LPS however it should be recognised that the actual number of homes required to "guarantee" a similar level of frequency response is likely to be far greater than 223 homes and will depend on a number of dynamic factors including the time of day of the event, seasonality, customer usage patterns and available storage in the devices at any given time.

Figure 3 shows the system frequency response when 4.6 MW diesel generator (red line) and equivalent FR-DSM (black line) are used during minimum demand. At 1s, 3.58 MW of wind generation is switched off resulting in the system frequency drop. The system frequency drops to 49 Hz with a rate of change of system frequency of 1.6 Hz/s in the case of the diesel generator (red line). To get a similar response about 1.96 MW of FR-DSM with the current dead-band (0.3 Hz) and droop characteristic (500% / Hz) is connected to the system. However, the rate-of-change of frequency is higher (1.8 Hz/s) in this case as the system inertia is lower (black line).

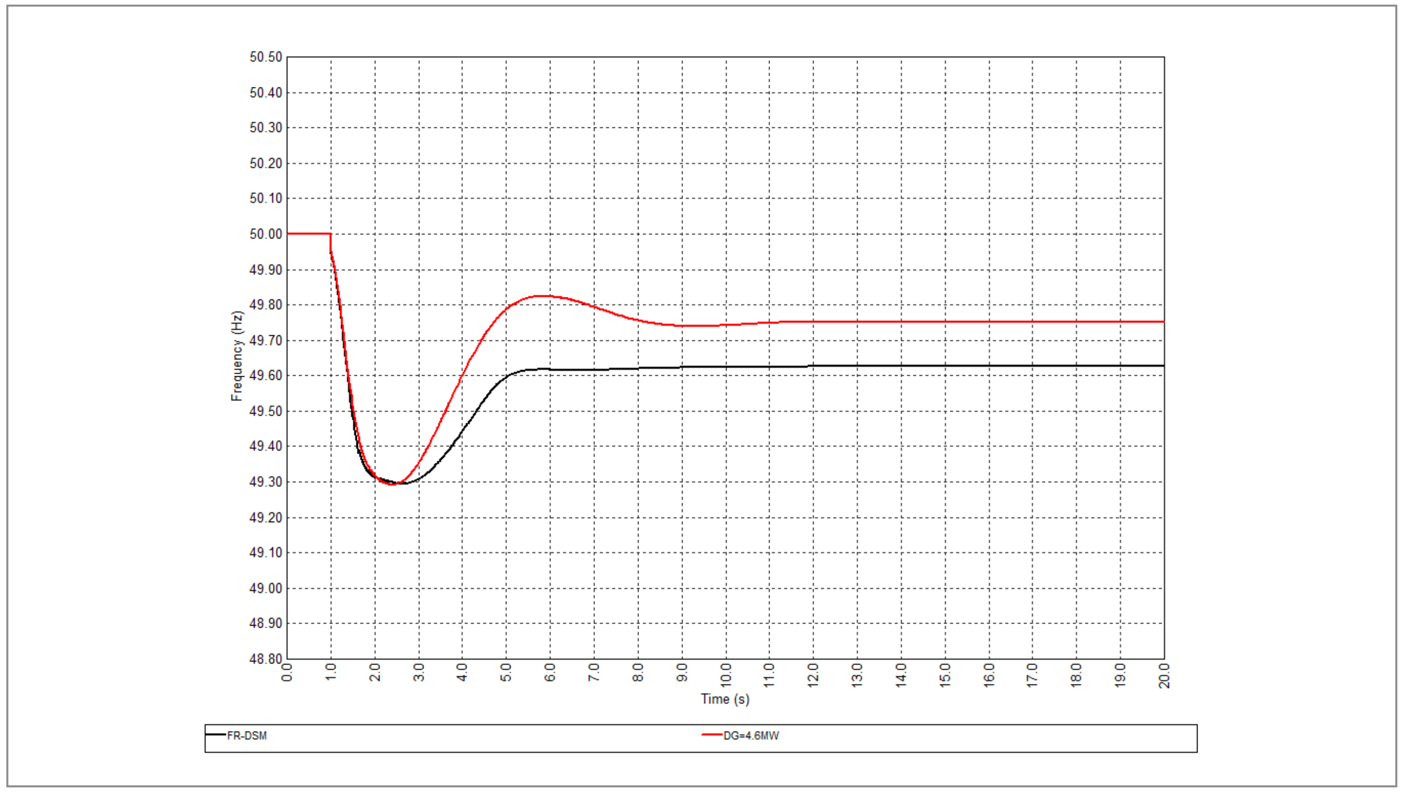

Figure 2 Frequency response during maximum demand after losing 7.94 MW of wind generation with 4.6-MW diesel generator (red line) and 1.637 MW of FR-DSM (black line).

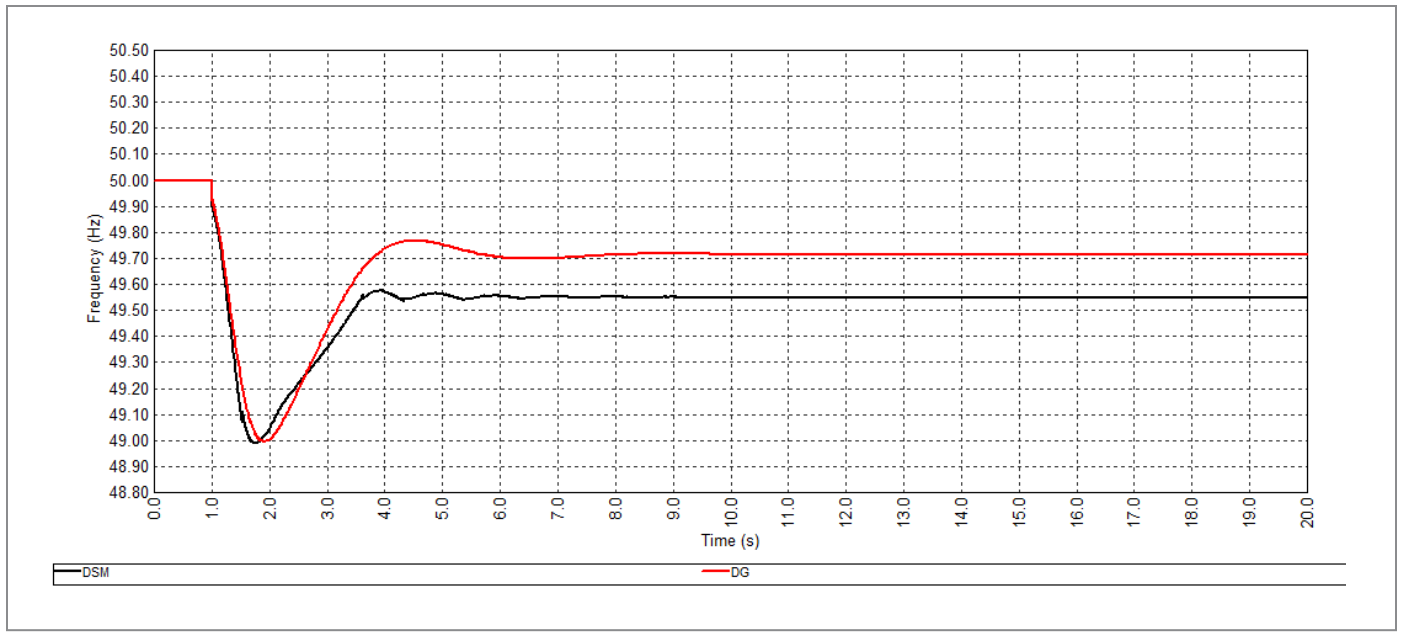

Figure 3 Frequency response during minimum demand after losing 3.58 MW of wind generation with 4.6 MW diesel generator (red line) and 1.96 MW of FR-DSM (black line).

From the above results, it is clear that the equivalent size of diesel generator required to provide the same response to FR-DSM is highly dependent on the available system inertia. During peak demand a diesel machine with a rating of 4.6 MW (G05) connected at LPS can provide a comparable response to about 1.64 MW of FR-DSM. During minimum demand, about 2 MW of FR-DSM is needed to provide a similar response to G05.

These results were obtained using the current FR-DSM settings (DB 0.3 Hz and droop of 500% / 1 Hz). However a higher amount of FR-DSM would be needed if a lower droop characteristic is used. Moreover, better frequency response is observed when a diesel machine is used as the rate-of-change of frequency decreases leading to better system stability.

2

Examples where the operation of the system has resulted in positive or negative effects on stability

2. Examples where the operation of the system has resulted in positive or negative effects on stability

The majority of under-frequency events in Shetland network are related to faults on the 33kV line 2L5, which results in SVT isolation from the rest of the network. At this time LPS units and Burradale wind farm have to cover most of the Shetland demand. An extreme event such as losing an SVT unit is also simulated.

2.1 Line 2L5 trip

The steady-state operating condition of the system before the disturbance is shown in Table 2.

The frequency response of the Shetland network after tripping the line 2L5 at 1s is shown in Figure 4. After tripping the line, the frequency dropped to only 49.42 Hz as a result of losing 4.5 MW which was supplied by SVT as shown in Figure 4 (red line). The system remains stable and the frequency of the system recovered by action of the online LPS units. However, if the line trip triggers the protection of Burradale wind farm after 1s, the system frequency collapses which is indicated by the blue line. The use of FR-DSM to prevent the network frequency from falling below the permissible limits is investigated with the existing and future FR-DSM levels. The simulation results show that about 4.2 MW of FR-DSM, which is 2.5 times the current FR-DSM, could prevent the system frequency from falling outside the statutory limits. This amount of FR-DSM is counted as 9% of the total system demand.

To examine if the current FR-DSM with full availability can have a positive impact on system stability, the trip of line 2L5 is followed by a less severe generation outage (trip of G21 at LPS). The frequency response of the Shetland network after tripping the line 2L5 at 1s and G21 at 2s is shown in Figure 5 (blue line). Although the system frequency recovers after tripping line 2L5 (red line), it cannot survive if the smallest generator (G21) protection at LPS is triggered by this incident (blue line). However, the system frequency could be kept within the limits if the current FR-DSM devices are used when they are fully charging as shown in Figure 5 (black line).

2.2 SVT unit trip

The steady-state operating condition of the system before the disturbance is similar to that illustrated in the previous section (Line 2L5 trip).

The frequency response of the Shetland network after tripping a unit at SVT at 1s is shown in Figure 6 (red line). After tripping the unit, the frequency declined with a rate-of-change of 0.17 Hz/s and exceeds the statutory limits. The system is also unstable if the current FR-DSM with full availability is used (blue line). However, implementing more FR-DSM could have a positive impact on system stability. The system frequency could be maintained within the limits if 4.2 MW of FR-DSM is integrated which is indicated by the black line in Figure 6. This amount of FR-DSM is accounted as 9% of the peak system demand.

Total demand	46.77 MW	Online LPS units	11, 21, 22, 23, and 24
SVT export	14.2 MW	Online SVT units	1 and 2
2L5 flow toward LPS	4.5 MW	Burradale wind farm	3.68 MW
Battery	Providing 1 MW		

Table 2 Pre-disturbance steady-state operating condition.

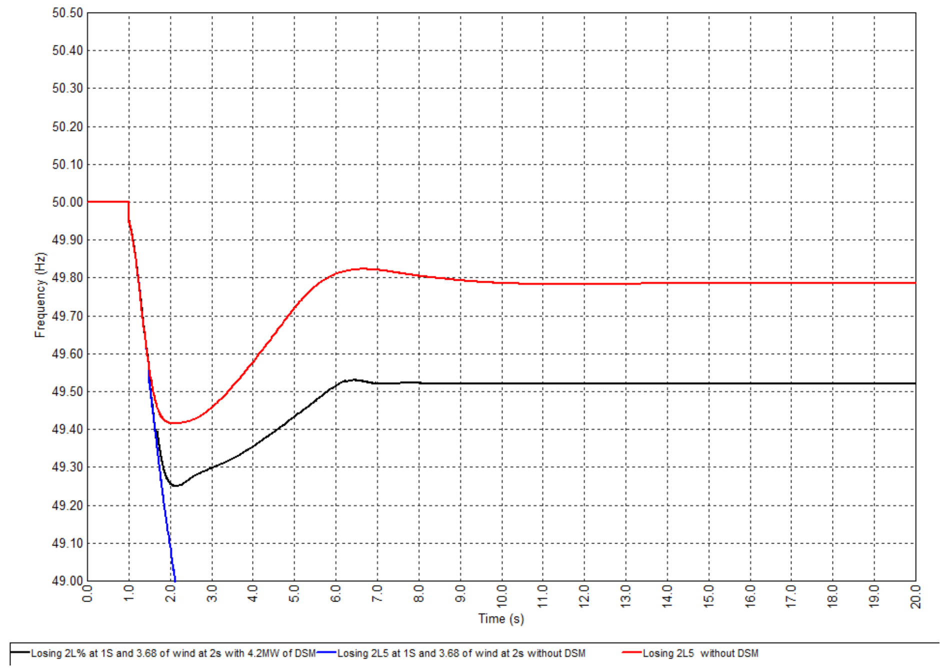

Figure 4 Event of losing line 2L5 without FR-DSM, losing line 2L5 and 3.68 MW of wind without FR-DSM and losing line 2L5 and 3.68 MW of wind with 4.2 MW of FR-DSM.

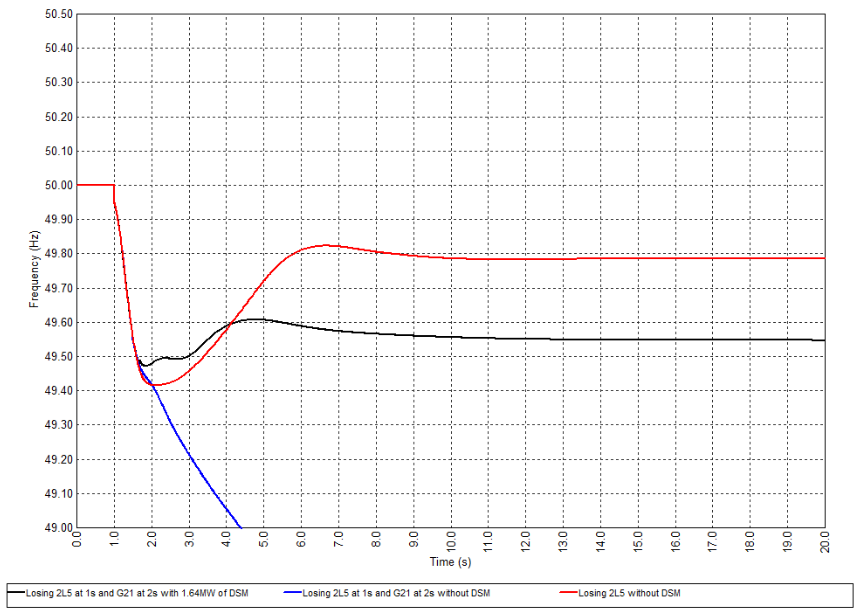

Figure 5 Event of losing line 2L5 without FR-DSM, losing line 2L5 and G21at LPS without FR-DSM and losing line 2L5 and G21at LPS with 1.64 MW of FR-DSM.

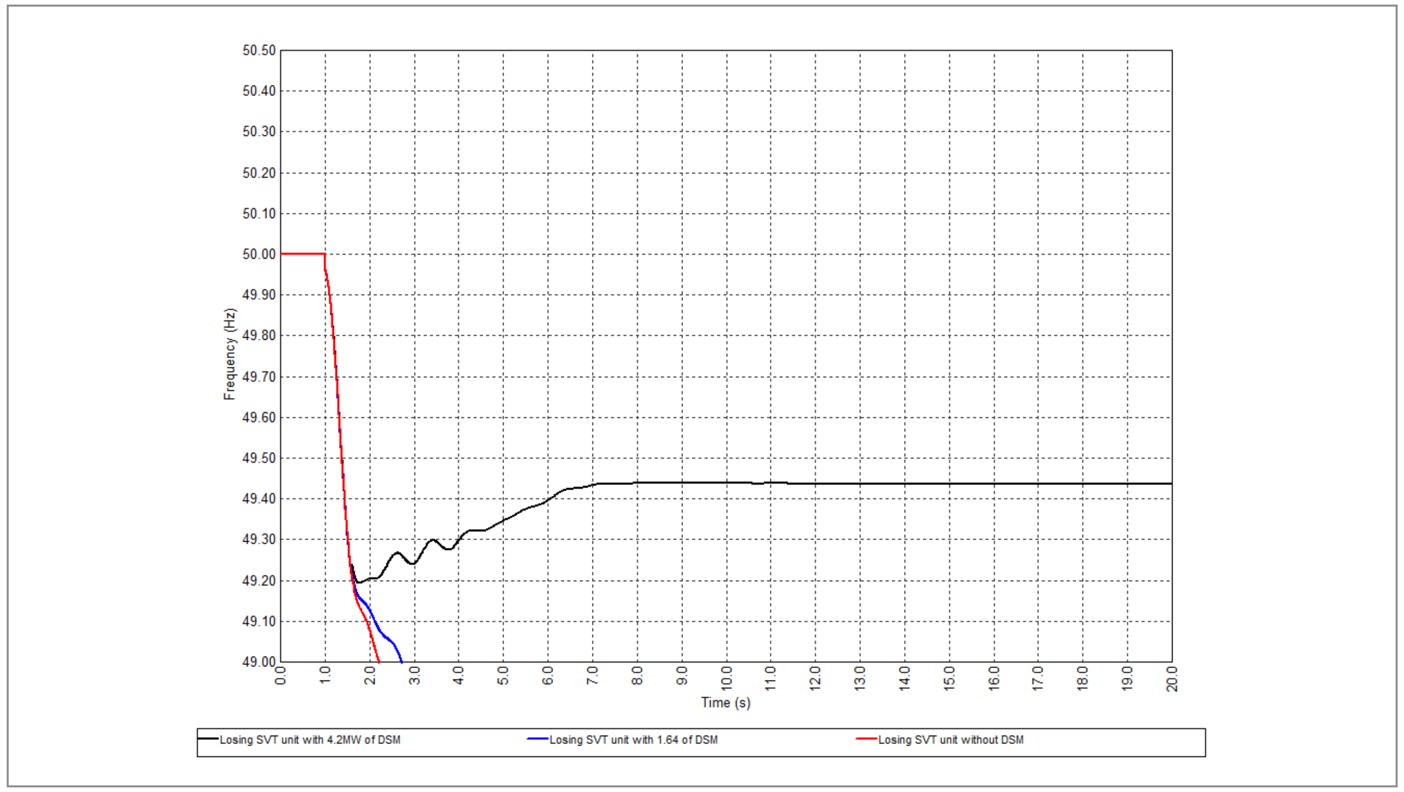

Figure 6 Event of losing generator at SVT without DSM, with current FR-DSM and with 4.2 MW of FR-DSM.

3

Conclusions and Recommendations

3. Conclusions and Recommendations

3.1 Conclusions

- The equivalent size of a diesel generator required to provide the same response to FR-DSM highly depends on the system inertia. The system inertia varies depending on the system load and which generators are online. For example, the system inertia during peak demand is higher than the system inertia during minimum demand as less generation is required to cover the minimum demand. Moreover, every permutation of online generators and each generator's output during a particular load results in a different system inertia to some extent. When the FR-DSM devices in the 223 homes are fully charging (1.639 MW) with the current settings applied, they can provide a similar level of frequency response to 1.6 MW of spinning reserve from an existing 4.6 MW rated diesel generator at LPS. The amount of required FR-DSM to provide an equivalent response to 4.6 MW diesel generator increases to about 2 MW during minimum demand which is the theoretical equivalent of around 300 homes fitted with FR-DSM appliances assuming the number of appliances per home would be the same as the average number currently fitted in the 223 homes and the appliances are all charging. The simulation results clearly show that the amount of FR-DSM required to provide a similar response to one of the existing diesel machines at LPS increases as the total system inertia decreases. In addition it has been shown that a diesel machine provides a better frequency response as the rate-of-change of frequency decreases leading to improved system stability.

- Some severe network disturbances result in large frequency deviations outside the statutory limits. As the majority of under-frequency events in Shetland network are related to faults on the 33kV line 2L5, the frequency response of the Shetland network after tripping line 2L5 was investigated. The simulation results show that if the line trip triggers the protection of Burradale wind farm, the system frequency falls outside the acceptable limits. The current amount of FR-DSM is too small to prevent the network frequency from falling outside the acceptable limits. However, theoretical results illustrate that this may be prevented by using at least 4.2 MW of FR-DSM, which could be achieved with around 600 homes fitted with FR-DSM appliances. Another severe disturbance scenario is tripping a unit at SVT. After tripping the SVT unit, the frequency declined below the statutory limits. The simulation results also demonstrate the current amount of FR-DSM is too small to prevent the network frequency from falling outside acceptable limits. According to this theoretical study, the system frequency could be maintained within the limits by using 4.2 MW of FR-DSM, which again could be achieved with an equivalent of around 600 homes fitted with FR-DSM appliances that are fully charging.

- Although theoretical numbers of homes required to provide suitable levels of spinning reserve or support to the network during periods of frequency deviation are noted above due to a number of dynamic factors, the actual number of participating homes that would be required to "guarantee" the availability of a suitable level of power from the appliances Is likely to be substantially higher than the theoretical numbers. Factors that would influence this would include time of day, seasonality and customer usage patterns.

3.2 Recommendations

- The frequency stability simulation results are highly dependent on the dynamic models used for the study, which should fully imitate the behaviour of the equipment deployed on the Shetland network. Therefore, it is recommended that power quality meters are installed in a number of locations in Shetland network to validate the existing module.

- The current amount of FR-DSM is too small to have a substantial impact on the frequency stability of the Shetland network especially when SVT is online. Moreover, as FR-DSM devices are usually charged during minimum load period between midnight and 5 am, the FR-DSM will not be beneficial if there is an under-frequency event during peak demand periods when there are no devices charging. Therefore, the frequency stability of the Shetland network could be enhanced by installing further FR-DSM and using 1-MW grid-scale battery at Lerwick station to provide a frequency response.

- A better understanding of the levels of customer participation is required to determine the levels of over-subscription needed to ensure the availability of a suitable number of FR-DSM appliances to provide a level of spinning reserve or support to the network during periods of frequency deviation, according to network conditions.

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