IMPACT OF DOMESTIC FREQUENCY RESPONSIVE DEMAND ON THE SHETLAND ISLANDS NETWORK FREQUENCY STABILITY

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ABSTRACT

This paper evaluates the impact of domestic frequency responsive demand (FRD) on the frequency stability of the Shetland Islands network and investigates the potential increase in wind generation that FRD may enable. To conduct this study a dynamic model of the Shetland network, including a FRD dynamic user defined model that reflects the physical characteristics of installed FRD, is implemented in dynamic simulation software. A number of scenarios derived by varying system demand levels, generator status, and the available FRD are considered. A performance assessment of network frequency stability has been conducted by observing the frequency nadir under different disturbances and operational conditions. The results of the preliminary studies suggest that installation of FRD benefits the Shetland system in terms of improving the frequency stability and that this may potentially allow additional wind generation to be accommodated, hence reducing reliance on fossil fuel consumption at the islands' main generation sources.

INTRODUCTION

Frequency deviation in a power system is the main indicator of the temporary imbalance between total generation and system demand. If the generated and consumed power are not in balance the frequency may change rapidly. The initial rate-of-change of frequency is determined by the inertia of the rotating masses of synchronous generators in the power system. The frequency deviation in a multi-machine power system is usually corrected by modifying the output of conventional synchronous plant through governor action [1, 2]. However, with high penetration levels of renewable energy resources, relying only on supply-side resources to perform frequency control becomes expensive and technically difficult [3]. Assisting in system frequency control from the demand-side presents a novel and viable way to complement the response of conventional generators [4].

In the UK, the project Northern Isles New Energy Solutions (NINES) by Scottish and Southern Electricity Networks (SSEN) explores the use of demand-side response to improve the frequency stability of the Shetland Islands distribution network through a number of innovative grid management technologies [5]. The Shetland's network is not connected to the GB electricity network and operates as an electrically islanded system (with associated operational issues) [6]. Shetland has significant wind potential making it an attractive area for wind power connections [7]. However, there are strict constraints on the ceiling for new wind generation connections in order to maintain system stability. Firm wind generation is limited to 4 MW to ensure that under all standard operating conditions the system can manage the loss of all wind generation without the system frequency breaching allowed limits.

Frequency stability of the isolated power system in Shetland is a major barrier which has to be overcome to allow additional wind generation connections. The NINES project has investigated a potential solution to improve the frequency stability using responsive flexible domestic demand in the form of electric space heaters with storage and electric hot water tanks. Both forms of domestic heating have the ability to operate as frequency responsive demand (FRD) managed through an Active Network Management (ANM) system.

The purpose of the work described in this paper is to provide an overview of the network modelling and analysis used in the NINES project. The paper also investigates how FRD can contribute to the secure operation of the Shetland network with high penetration of wind generation. Early results are presented and discussed which will give estimates on the potential amount of wind generation that could be integrated with the help of FRD.

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.

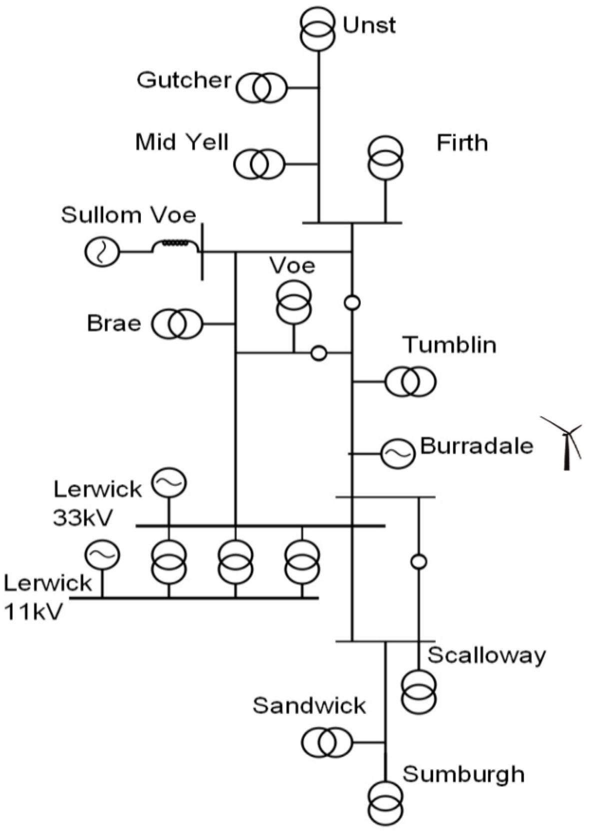

Figure 1 Schematic representation of the 33kV Shetland network including the location of primary substations and generation sources.

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 (BWF). LPS consists of nine diesel generators and two gas turbines with sufficient capacity to meet the total peak system demand (although a tender for a replacement solution is currently being sought) [8]. 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. BWF with an installed capacity of 3.68 MW consists of five doubly-fed induction generator (DFIG) wind turbines. BWF is connected under a firm connection agreement and operates at 52% capacity factor due to the excellent wind resource on Shetland [9].

SYSTEM STABILITY RULES

Power system networks are commonly subjected to voltage, transient stability and thermal constraint issues. However, the operation of remote isolated networks is subjected not only to these common issues, but also critical frequency constraints which can limit the penetration of wind power [6]. The unexpected loss of wind power in small power systems, such as Shetland system, can cause significant fluctuations in the system frequency. The system operator in Shetland has identified three related stability issues:

- The LPS units should provide a minimum of 40 % of the current Shetland demand at all times. This rule – developed through operational experience – is used to ensure voltage levels across the network are maintained within limits as LPS engines, together with two capacitor banks, are the main source of reactive power. Therefore, additional wind generation can be limited by this rule especially during minimum demand.
- Spinning reserve is required to cover the sudden loss of wind generation, which means limiting wind generation to the current headroom of conventional generators. For a given dispatch of conventional generation, an increase in demand leads to a reduction in headroom and therefore a reduced limit on wind generation.
- Shetland network is required to comply with the GB Grid Code in the same way as the rest of the UK. Therefore, the system frequency should be maintained within limits (1% of the nominal level of 50 Hz) unless exceptional circumstances prevail.

FREQUENCY RESPONSIVE DEMAND

As Shetland does not have access to mains gas, most of the domestic properties currently have heat provided by electric space and water heaters. These heaters are controlled (on or off) via a radio tele-switching scheme [10] to spread the load from these heaters across the day. As the main aim of NINES project is to support wind generation and enhance frequency stability of Shetland network, some of these space and water heaters were replaced with smart heaters. The installed smart heaters can vary their load in response to a frequency disturbance according to predefined settings. In Shetland, about 228 homes have been equipped with Dimplex space and water heating appliances which can be used to provide frequency support [11]. The controller in these appliances measures the mains frequency and acts accordingly if the mains frequency drifts outside the specified dead-band. A modified power is calculated according to the degree of frequency variance outside the dead-band and frequency response droop shown in Figure 2.

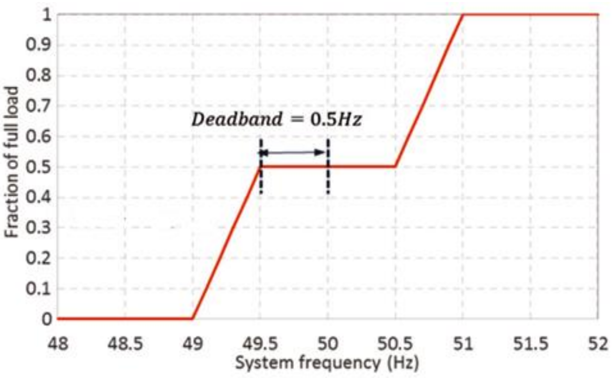

Figure 2 The frequency responsive characteristics of FRD

Each home equipped with smart heating is capable of providing an average of 7.19 kW of FRD. These appliances are managed through the ANM system to store energy in homes during periods of excess electricity supply.

To investigate the relationship between intermittent generation and the responsive demand used to support the system frequency, a user-defined model for dynamic simulation has been created to reflect the FRD characteristics and the current settings. The FRD is modelled to replace existing demand (not as additional system demand). The response time of FRD is a critical factor for system frequency stability. In 2012 SSEN issued guidance on Domestic FRD stipulating a response time of 400ms. These response time is comparable to National Grid's 2016 tender for enhanced frequency response [12]. To validate the FRD response time, devices were tested by Queen's University Belfast. Results calculated an average response time between the frequency excursion state being flagged on the appliance and the load switching of 350ms. This is inclusive of the frequency measurement on the Dimplex space and water heating appliances which takes place at every 200ms. The current droop setting of the installed FRD is 500%/Hz with a dead-band of 0.3 Hz.

SHETLAND FREQUENCY STABILITY ANALYSIS AND DISCUSSION

Offline dynamic simulations were carried out with high resolution to investigate the benefits FRD can contribute to the Shetland network frequency stability. To calculate a theoretical maximum penetration level of wind power, a number of simulations studies were conducted based on the dynamic modelling of the most relevant components of the Shetland's power network. Simulations studies assess the dynamic performance of the network at different demand levels and a specified level of wind generation. The wind generation is disconnected and the system response evaluated. In this paper, transient frequency of the Shetland network should be maintained within ±2% of 50 Hz in the event of losing the maximum connected wind generation for a given set of conditions. The ±2% limit is used here for illustration purposes only to show how FRD may contribute to frequency stability of the Shetland network.

To investigate the frequency response of the Shetland network, a critical scenario (SVT offline) is investigated. Circumstances whereby SVT is offline and wind is allowed on the network is not necessarily a scenario that would occur in real life on Shetland and is used for illustrative purposes only to investigate the impact of FRD on the frequency stability of the Shetland network. In this scenario, the frequency of the Shetland network is supported only by online units at LPS. The frequency of the system is observed under sudden loss of wind generation for each demand level. The disconnection of the existing BWF (3.68 MW) and also incremental increases of future wind power plant connections were investigated to establish a theoretical maximum permissible level of wind generation. A steady-state condition is maintained for the first second and then a disturbance is applied by disconnecting all the wind generation. The system frequency is observed and plotted in Hz for 20s.

The frequency response of the Shetland network during maximum demand after losing 3.68 MW from the BWF is shown in Figure 3 (blue line). The initial results indicate that the frequency deviation after losing BWF is still within the predefined transient frequency limits (for illustration purposes assumed at ±2%) and the network could accommodate higher amounts of wind generation (up to a theoretical permissible level of 7.94 MW). The red line in Figure 3 is the system response to losing 7.94 MW of wind and results in approximately a 2% frequency deviation. Therefore, the maximum theoretical wind generation that could be connected without degrading the system frequency stability in the event of losing the entire wind generation is about 7.94 MW.

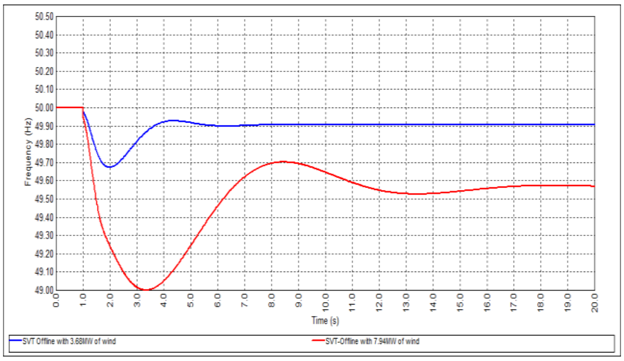

Figure 3 Frequency response during maximum demand after losing 3.68 MW and 7.94 MW of wind.

Frequency response is examined further during maximum demand after losing 7.94 MW of wind power with and without support from the current FRD. Figure 4 shows the frequency response improvement at maximum demand when 1.639 MW of FRD is used (calculated as 228 homes with FRD capability times the individual average output power of 7.19 kW). The frequency nadir improved from 49 Hz (without FRD) to about 49.3 Hz (with FRD). As the frequency response of the Shetland network is enhanced by the connected frequency responsive loads, more wind generation is allowed to be connected. When heating elements are fully charging in the 228 homes, the total wind generation that may be allowed to be connected is 9.3 MW, an increase of 1.36 MW from the case with no FRD.

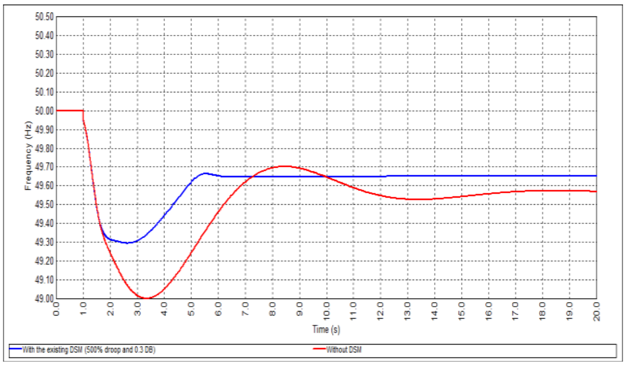

Figure 4 Frequency response during maximum demand after losing 7.94 MW of wind generation without and with 1.639 MW of the responsive demand.

The analysis was also carried out for minimum (13.05 MW) and average (29.47 MW) demand levels with FRD, showing improvements in system frequency response for both cases. Potential wind generation connections increased from 6.5 MW to 7.83 MW for the average demand level and from 3.58 MW to 4.2 MW for the minimum demand level (without and with DSM, respectively).

However, the system frequency improvements provided by FRD are highly dependent on the availability of FRD, which varies during the day and throughout the year. Therefore, the frequency response was also examined with real measured data of DSM availability (provided by Shetland's system operator). For this purpose data recorded on 1/1/2016 is used, which shows a maximum power available to provide frequency response of 434 kW in that particular day.

Frequency response is examined again during maximum demand after losing 7.94 MW of wind power with support from the measured 434 kW of FRD. The frequency nadir improved from only 49 Hz to 49.09 Hz as shown in Figure 5. As the amount of FRD used in this case is smaller than the previous case, the system frequency has little improvement (about 0.1 Hz). This improvement will be reduced further if a lower amount of FRD is used.

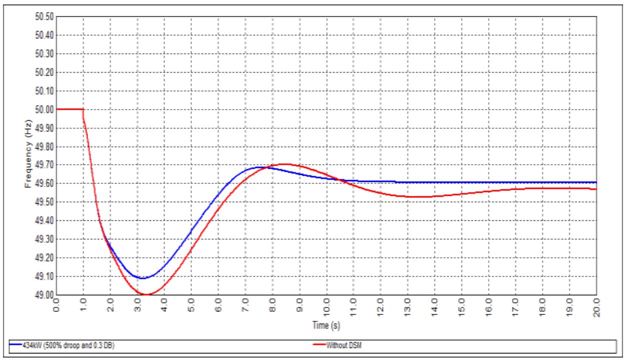

Figure 5 Frequency response during maximum demand after losing 7.94 MW of wind generation without and with 434 kW of the responsive demand.

The previous simulation results for each demand level are summarised in Figure 6. These values are obtained by using a specific FRD characteristic and settings (500%/Hz with a dead-band of 0.3 Hz). Other FRD characteristics and settings may result in different values. Moreover, the availability of FRD is playing a very important factor in supporting system frequency. FRD can provide better frequency response during the winter season when the availability of FRD would be higher than the rest of the year. However, less frequency support could be provided by FRD during summer time when many space heaters are switched off.

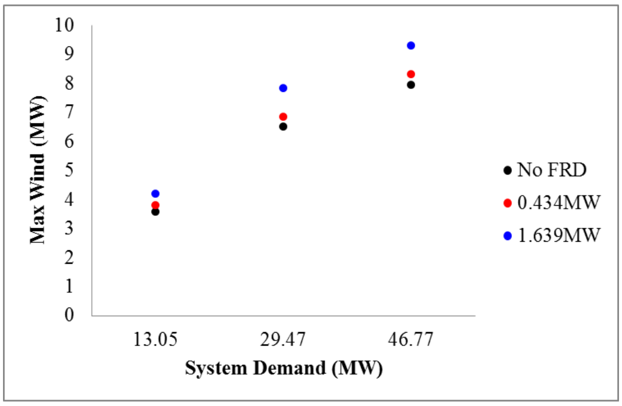

Figure 6 Maximum wind generation for each demand level with different FRD penetration levels.

The calculated frequency stability rules have to be linearized as the software deployed for the NINES project requires the stability rules to be defined in a linear form. System demand cannot be measured directly in real time and instead the total generation is used instead.

An estimate of the theoretical amount of wind generation that could potentially be connected for every 1 MW of available FRD is different for each demand level, and therefore it is difficult to form a linear equation. However, an estimation of two linear equations could be provided. According to Figure 6, the estimated linear relationship between the maximum amounts of wind generation that can be connected while FRD is participating in frequency response can be written as follows.

For demands between minimum and average demand levels:

$$P_{wind}^{max} = 0.1293P_{Fixed\ demand} + 0.3701P_{FRD} + 1.9135 - P_M$$

For demands between average and maximum demand levels:

$$P_{wind}^{max} = 0.1293P_{Fixed\ demand} + 0.8298P_{FRD} + 1.8926 - P_M$$

Where $P_{Fixed\ demand}$ is the total system fixed demand, P_{FRD} is the amount of FRD participating in frequency response and P_M is an additional safety buffer between the calculated limit and operational limit.

CONCLUSION

In this paper, the impact that domestic FRD would have on the frequency stability of the Shetland network was explored. The potential increase in the maximum capacity of wind generation that the FRD may allow was also investigated. It has been shown that FRD has the potential to support frequency stability and hence allow more wind power penetration. The simulation results show that the current wind capacity connected on Shetland has the potential to be increased with suitable support from FRD. When heating elements (space and water heaters) are fully charging in the 228 homes, the total wind generation that is allowed to be connected increased by 1.36 MW from the case with no FRD.

ACKNOWLEDGEMENTS

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