Abstract. Isolated power grids lack of external support, show low inertia constants and have insufficient frequency regulation. Therefore, frequency excursions after an active power mismatch are severe. Traditionally, synchronous generators have been the active power and frequency control contributors in power systems. Though, as an emergency solution, load shedding is a frequent practice in island grids, in order to prevent frequency collapse. Currently, renewable generation based on non-synchronous generators is requested in some grid codes to participate in the active power-frequency control. This feature is especially interesting in isolated power systems with great wind potential. This paper presents the simulation results of a typical small size isolated power grid model in order to study frequency stability. In addition, the contribution of a wind farm in the frequency control of the system has been studied through curtailment control mode at wind turbine level.

Key words
Isolated power systems, wind power generation, frequency regulation, curtailment, load shedding.

1. Introduction

In isolated power systems, a reduced number of generators are normally connected to the system, mostly fed by diesel or heavy oil generating units in small or medium size islands. Therefore, islands face extreme challenges from an energy security perspective, as they are dependent on petroleum derived fuels. The integration of renewable energy sources into the power mix is called to be a solution, especially in islands with a great potential in renewable energies, such as wind power.

However, the small size and lack of external support of isolated power systems could result in frequency stability issues, especially in islands with high renewable energy penetration, which show low inertia constants and insufficient primary frequency regulation. Nowadays non-synchronous generators, such as wind turbines, are requested in some grid codes to participate in the active power-frequency control.

This paper analyses the impact of high ratios of wind power penetration in the frequency response of a typical small size isolated power system after a loss of generation event. Besides, the participation of a wind farm in the frequency control of the system has been studied through curtailment and droop control at wind turbine level. Section 2 describes frequency control mechanisms in isolated power grids. Section 3 introduces the modelling of the test grid under study and finally, simulation results are shown in Section 4.

2. Frequency control in isolated power systems

A. Frequency regulation basics

Disturbances causing a power imbalance between demand and generation result into frequency excursions in the system. After a generator trip, frequency drops. In small isolated power systems, a single generator can represent a sizeable proportion of the total generation. Therefore, large power imbalances relative to the system are frequent.

A frequency drop event shows three main characteristic parameters (Fig. 1): rate-of-change of frequency or initial frequency gradient, minimum frequency also called frequency nadir, and the steady-state frequency deviation.

Fig. 1. Frequency deviation after a generator trip
In the first few seconds following the loss of a large power plant, the grid frequency starts to drop. The initial frequency dynamics is dominated by the inertial response of the generators that remain online. So, the initial frequency gradient is determined by the inertia present in the power system and the active power mismatch, as indicated by the swing equation in (1). Load damping has been neglected in the equation.

\[
\frac{d\Delta \omega}{dt} = \frac{\Delta P_m - \Delta P_c}{2 \cdot H}
\]  

(1)

Isolated power grids have inherently lower inertia constants, and therefore, the initial rate of change of frequency is usually higher. In addition, generators in islands are usually large compared to the system load. That is why any outage results in large active power mismatches.

The reason frequency stops declining at the minimum frequency (point B in Fig. 1) is due to a combination of system inertia, load/frequency, and governor response [1]. Finally, at point C in Fig. 1, the system reaches a steady-state, determined by the droop characteristic of the generators, as indicated in (2).

\[
\Delta f = -\Delta P \cdot R
\]  

(2)

Frequency deviation in steady-state can be calculated in function of the power imbalance in the system \(\Delta P\) and the equivalent droop constant \(R\) of the power system. A poor regulation capability in a power system will lead to large steady-state frequency errors.

These three stages in frequency decay occur during the first seconds after a generator loss and are related to primary control [2]. However, for large disturbances, primary frequency control is usually not fast enough to restore power balance and to limit frequency excursions within acceptable limits. In addition, spinning reserve in isolated power systems is often insufficient to restore lost generation. The power system’s last resort to arrest frequency deviation consists in shedding load.

Primary control is complemented by secondary and tertiary control. Secondary Control typically includes the balancing services deployed in the “minutes” time frame, and most commonly carried out by means of Automatic Generation Control (AGC). Last, tertiary reserve is the additional active power available from 90 seconds to 20 minutes subsequent to the event [2].

B. Active power-frequency control in wind farms

Traditional active power and frequency control contributors in power systems are synchronous generators. However, non-synchronous generators, such as wind turbines, are nowadays requested in some grid codes to participate in the active power-frequency control. This feature is especially interesting in isolated power systems. As an instance, the Irish grid code requires wind plants to have active power curtailment capabilities, and outlines specific active power generation set points in the event of a frequency deviation [3], as displayed in Fig. 2.

The control schemes can be divided into a three-level hierarchy, i.e. wind turbine, wind farm and power system level controls [4]. At the wind turbine level for primary control, existing active power control strategies include power output control or curtailment, ramp rate control, and adjustable droop control for under/over frequency regulation [5].

In addition, rapid injection of energy would also be required after sudden frequency drop in order to forestall load shedding and generator tripping, especially on island systems. Synthetic inertial response could be the answer. The approach in inertial control is to modify the wind turbine controller so as to deliver a response similar to that from the inertia of synchronous machines in response to changes in network [6].

At wind farm level, local control can be implemented by energy storage systems (ESS) connected at the Point of Common Coupling (PCC) of the wind farm, or individually in the Wind Turbine Generators (WTGs). To enable WTGs to effectively participate in frequency and active power regulation energy storage devices will be required to dynamically match the intermittency of wind energy [7], as well to improve inherent frequency response of wind farms. Compared to most commonly used energy storage systems (pumped water and compressed air), batteries and ultracapacitors are more efficient and have a quicker response [7], which is of higher importance for frequency stability issues.
3. Power system description and modelling

A. Power system model

The modelling and simulation study has been carried out on a small size isolated system using the PSS/E software [8]. The test grid modelled is based on [9]. It is a 63 kV based network, with similar characteristics to those found in typical small size isolated power systems. Fig. 3 shows the single-phase scheme of the power system under study.

![Isolated power system model under study](image)

The generation system consists of a thermal power station made up of three generating groups with a total installed capacity of 60 MW and an individual inertia constant of 2.5 s, and a diesel generator set of 15 MW with 2.08 s of inertia. Frequency response in the power system after the disconnection of the diesel generator has been studied. The impact of a wind farm, modelled as aggregated full converter wind turbines, in frequency stability has been assessed. Table I indicates the PSS/E library dynamic models used for simulation purpose.

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>PSS/E MODELS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power station</td>
<td>GENROU, SEXS, TGOV1</td>
</tr>
<tr>
<td>Diesel generator set</td>
<td>GENROU, SEXS, DGOV1</td>
</tr>
<tr>
<td>Wind turbines</td>
<td>WT4G1, WT4E1</td>
</tr>
</tbody>
</table>

B. Under frequency load shedding

Also, a simple three step under frequency load shedding (UFLS) system has been implemented, using the PSS/E library dynamic model LDSHAL. The triggering criterion is purely based on frequency and the rate of change of frequency is not used.

Reference [10] reviews different UFLS practices and concludes that load under relief is usually divided into three to six discrete blocks with frequency thresholds in the range of 48 to 49 Hz in the case of larger systems and with frequency thresholds between 47 and 49 Hz for smaller power systems, such as the power system under study. Further, these discrete blocks correspond to step sizes of 5% to 15% of system demand per step. The UFLS implemented in the power system model under study has been parameterized according to practical values in isolated power grids, and it is indicated in Table II.

<table>
<thead>
<tr>
<th>N. STEP</th>
<th>FREQUENCY THRESHOLD</th>
<th>SHED LOAD</th>
<th>PICK-UP TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48.25 Hz</td>
<td>15%</td>
<td>0.1 s</td>
</tr>
<tr>
<td>2</td>
<td>47.75 Hz</td>
<td>15%</td>
<td>0.1 s</td>
</tr>
<tr>
<td>3</td>
<td>47 Hz</td>
<td>15%</td>
<td>0.1 s</td>
</tr>
</tbody>
</table>

C. Wind farm power curtailment

Power curtailment in the wind farm has been implemented adding a user model in PSS/E, which controls the active power reference of the WT4E1 model. In steady-state, the wind farm generates active power, curtailed by 20% of the nominal capacity. However, if frequency deviation exceeds 0.01 p.u., wind turbines modify their production following a droop control characteristic, with 5% droop.

D. Study cases

Table II summarizes the simulation cases carried out for this study. The base case is considered for the isolated power system without wind power generation.

<table>
<thead>
<tr>
<th>STUDY CASE</th>
<th>WIND POWER PENETRATION (%)</th>
<th>SPINNING RESERVE</th>
<th>CURTAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20%</td>
<td>3 machines</td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>40%</td>
<td>3 machines</td>
<td>x</td>
</tr>
<tr>
<td>3</td>
<td>60%</td>
<td>3 machines</td>
<td>x</td>
</tr>
<tr>
<td>4</td>
<td>20%</td>
<td>2 machines</td>
<td>x</td>
</tr>
<tr>
<td>5</td>
<td>40%</td>
<td>2 machines</td>
<td>x</td>
</tr>
<tr>
<td>6</td>
<td>60%</td>
<td>2 machines</td>
<td>x</td>
</tr>
<tr>
<td>7</td>
<td>20%</td>
<td>3 machines</td>
<td>√</td>
</tr>
<tr>
<td>8</td>
<td>40%</td>
<td>3 machines</td>
<td>√</td>
</tr>
<tr>
<td>9</td>
<td>60%</td>
<td>3 machines</td>
<td>√</td>
</tr>
<tr>
<td>10</td>
<td>20%</td>
<td>2 machines</td>
<td>√</td>
</tr>
<tr>
<td>11</td>
<td>40%</td>
<td>2 machines</td>
<td>√</td>
</tr>
<tr>
<td>12</td>
<td>60%</td>
<td>2 machines</td>
<td>√</td>
</tr>
</tbody>
</table>

The loss of the diesel generating unit in time instant $t=2$ s has been simulated to study frequency excursions in the system under three wind power penetration scenarios: 20%, 40%, and 60% of the total demand in the system, which amounts to 55 MW. Different possible combinations of the synchronous generators have also been tested to cover the remaining demand, resulting in different spinning reserve available in the system and different equivalent inertia. This feature is implemented considering the thermal power plant with two or three machines connected.

In addition, the simulation cases study the effect of shedding load during a frequency excursion, as well as the participation of the wind farm in frequency control,
simulated through curtailment control implemented at wind turbine level.

4. Simulation results

A. Impact of wind power penetration level in frequency excursion

Renewable generation does not inherently contribute to the system inertia as it is generally constituted of small units with lower inertia than traditional power units. However, conventional power units are being replaced in areas with great potential in renewable energies such as wind. It is the case in some island grids. This paper aims to analyse the impact of wind power in frequency stability in a small size isolated power grid.

Fig. 4 shows the frequency deviation in p.u. after the trip of the diesel generating unit at instant \( t=2 \) s. Frequency response is shown to be very similar for the three first cases plotted out: base case with 0% wind power, study case 1 with 20% of wind power and study case 3, with 40% of penetration. In fact, the overall system inertia is similar as because the same thermal units are in service. However, frequency excursion is abrupt and deeper for the scenario in study case 4, with a medium penetration level of wind generation of 20% but with only two machines of the thermal power station online, which leads to a lower system inertia value. Therefore, it can be concluded that wind power generation does not impact significantly in frequency stability, provided that enough synchronous generation remains connected in the system.

Fig. 4. Impact of wind power penetration in frequency deviation (p.u.)

B. Load shedding in the isolated power system under study

Load shedding is a frequent practice in island grids as an emergency solution to arrest frequency drop in case of generation trip. Fig. 5 shows the consequence of shedding load in the island power system under study. The study cases 1 to 6 (see Table II ) with different wind power penetration have been compared, disabling or enabling UFLS. The emergency action of disconnecting load arrests frequency decay in the system. So, frequency does not reach such deep values, and during recovery, nominal frequency is almost attained. Therefore, frequency error in steady state before secondary and tertiary control action is also lower. However, in study case 4, even with UFLS, the frequency excursion increases comparatively, as the rate of change of frequency is higher. So, during the pick-up time of the UFLS, frequency decreases faster than in study cases 1 and 3, and a lower frequency nadir is reached before load is shed.

Fig. 5. Frequency deviation upon the action of UFLS (p.u.)

Fig. 6 displays active power in each bus of the power system model, without and with UFLS. As shown in Fig. 6, the first step of the UFLS is enough to prevent frequency from collapsing and only 15% of the total demand is shed after frequency remains under 48.25 Hz longer than the configured pick-up time 0.1 s. Load is shed disconnecting 15% of the demand in each bus of the system.

Fig. 6. Active power (p.u.) in each bus of the power system model, without and with UFLS

C. Wind power curtailment and frequency stability

Operating wind turbines under the available wind capacity, provides a power reserve that can be used to prevent frequency instability. In consequence, in case of a frequency dip WTGs are able to increase their production and operate to their full capacity. Fig. 7 shows the power output of the wind farm for study case 9.
Initially, the WTGs are generating 80% of the installed capacity, which is 60% of the total demand: 16 MW. Upon the disconnection of the diesel generating unit, frequency drops suddenly. Therefore, applying a droop control mode, WTGs increase their production, finally amounting to 100% of the installed capacity: 20 MW. Therefore, active power mismatch in the system decreases and frequency response improves.

The simulation results show that wind power generation does not impact significantly in frequency stability, provided that enough synchronous generation remains connected in the system. However, higher wind power penetration levels could be reached in island grids if WTGs would operate in curtailment control mode. This way, frequency limits would be respected and less load would be interrupted through UFLS, increasing the under frequency load-shedding margin.

### Acknowledgements

The authors acknowledge the financial support from the Ministerio de Ciencia e Innovación of Spain, project IPT-2011-1142-920000 (subprogram INNPACTO) and the University of the Basque Country UPV/EHU (UFI 11/28).

### References