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# Icelandic Operational Experience of Synchrophasor-based Fast Frequency Response and Islanding Defence

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## SUMMARY

The Icelandic power system experiences large and rapid frequency deviations because of its low inertia and large loads relative to the system size. Using fast synchrophasor based signals to trigger new flexible demand- and supply-side resources, fast response services can reduce frequency deviations and the probability and impact of islanding. This paper reports on the experience of the first live operational fast response services addressing angle and frequency stability. The approach improves reliability and access to the grid in constrained locations.

Flexible resources in supply and demand side can initiate power responses very quickly, and existing resources are more cost effective than deploying new facilities such as storage. Incorporating them requires flexibility and co-ordination by the Transmission System Operator (TSO). Landsnet, the Icelandic TSO, is field testing fast wide area control as a partner in the EU MIGRATE project [1], along with generation and consumer collaborators.

Iceland's electrical energy is supplied by 73% hydro and 27% geothermal resources [6]. Hydro generation can be ramped, and geothermal resources have fast-valving capability for severe disturbances. At the demand side, large thyristor-controlled aluminium smelter loads can be stepped up or down almost instantaneously, while other loads can accept fast acting tripping. Fast synchrophasor measurements are used for real-time identification of the occurrence, impact and location of a disturbance, and response is applied to counteract the stability impact. The relative values of time to respond and location sensitivity are discussed.

Other countries share concerns with low inertia. Inertia is reducing in the GB system with increasing renewable generation, and a similar flexible fast response capability is being trialled [2], as well as a battery storage service [3]. South Australia has low inertia and a weak transmission link to Victoria. A 100MW battery storage solution was recently installed, providing fast frequency response [4]. In Ireland, new ancillary services are defined to reduce constraining-on synchronous generation [5]. The Icelandic approach using novel control of existing capacity is relevant to many operators with concerns over inertia or stability.

**KEYWORDS**
Inertia, frequency control, synchrophasors, wide area control, stability, governor, demand response.

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## THE NEED FOR FAST RESPONSE FOR ANGLE AND FREQUENCY STABILITY

Frequency stability involves containing the frequency peak after a disturbance, and in Iceland this requires a response to match the loss within about 4-7s. However, fast response impacts angle stability, which defines whether the system will split or remain synchronised. Accelerating frequency response to act within the timeframe of the first angle swing (typically around 1.5s in Iceland) requires a control approach that is sensitive to the location of the disturbance and the angle behaviour.

Figure 1 illustrates the conventional view of a frequency disturbance and the action of primary and secondary control to limit the frequency drop and restore near-nominal frequency. Conventional primary frequency response is based on governor frequency control and is typically delivered in 10-20s, limited by physical turbine and governor constraints.


**Figure 1 Conventional frequency response services**

There are four concerns related to conventional control:

1. In common with other low inertia grids, Icelandic frequency can reach very high values in a short time, as shown by the 53Hz peak in Figure 3 around 4 seconds after the disturbance. Turbine governors tend to be too slow to arrest the frequency before the deviation becomes very large.
2. Reducing the response time of conventional control will tend to destabilise grid frequency; sustained oscillations between 49 and 51Hz with 30 second cycle period have been observed in Iceland and elsewhere [7].
3. Response within the first 2 seconds of a disturbance interacts with the transient angle response and can either improve or degrade the risk of islanding, depending on where the disturbance occurs relative to the response.
4. Response far from the source of the disturbances can lead to increased loadflow and may trip overload protection.

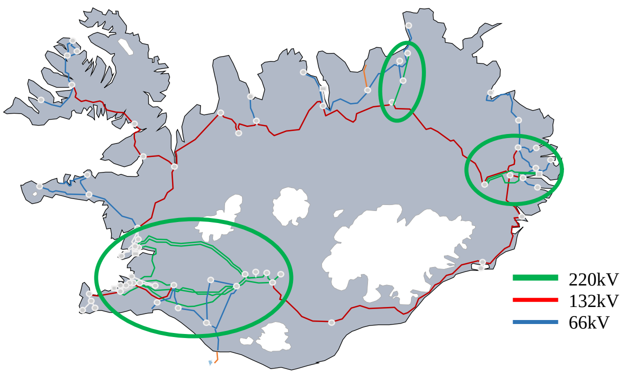


**Figure 2 Icelandic transmission system showing main 220kV centres of inertia**

An example of a trip of a large load is shown in Figure 3. The acceleration is unequal across the grid, earlier and faster close to the initial loss of load than at distant locations in the grid.

This difference in frequency results in angle differences increasing between east and west, and results in protection tripping to avoid an out-of-step condition. In the event in Figure 3, the network separates at around 1.2s from the main disturbance, and frequency in the southwest island reaches a peak of 52.8Hz four seconds after the disturbance.

A fast frequency response of increasing load or reducing generation is only helpful for the disturbance in Figure 3 if it is within the southwest area of the grid, i.e. in the area of the disturbance. Applying response in the east would increase the angle separation between the grid regions, making overloads and splitting more likely, and producing greater power imbalance in the resulting islands.

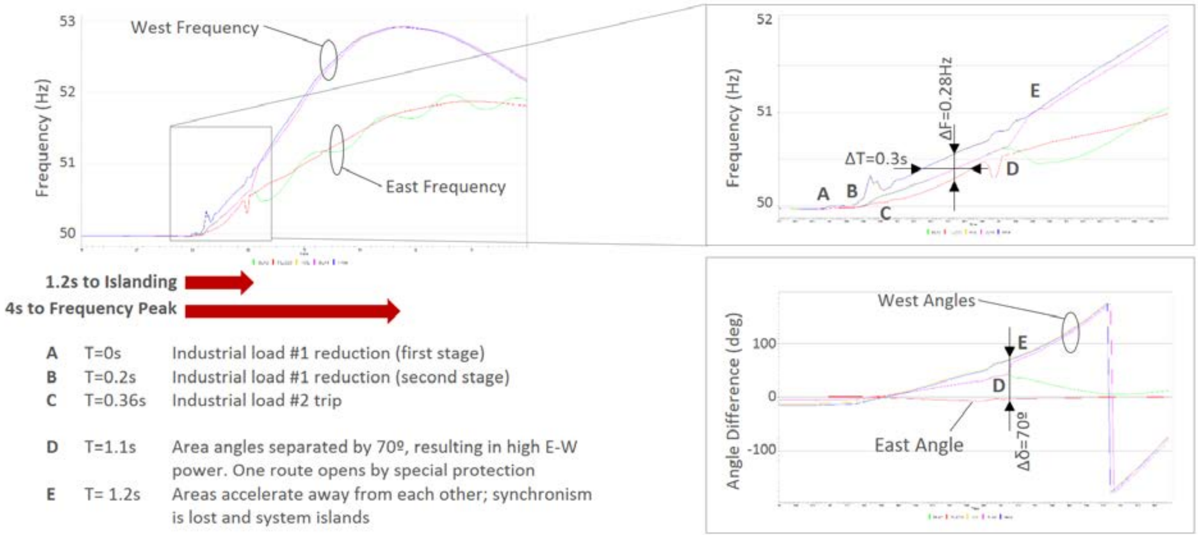


**Figure 3 Example of Load Loss Event leading to Islanding**

## WIDE AREA CONTROL MECHANISM FOR FAST RESPONSE

The principle of using aggregated voltage phasors and frequency to represent the coherent areas of the grid is shown in Figure 4. The aggregated phasors are a simplified and fault-tolerant way of representing the power system in measurements that can be shared with all fast response controllers. The controllers are activated using these measurements, deriving a system-wide Rate of Change of Frequency (ROCOF) for proportional response (accounting for islanding status), using the aggregated values to enable or inhibit response per area. The main elements of the control scheme are shown in Figure 5, with the following components:

| | |
|---|---|
| Phasor Measurement Units (PMUs) | Synchronised voltage and current measurements at 20ms updates. 45 PMUs are connected in Iceland, of which 7 are currently used in the control scheme. |
| Regional Aggregator (RA) | Aggregates the PMUs within each region in Figure 4, to produce a single angle and frequency value representing the region. Aggregated signals are shared with all Resource Controllers. RAs provide redundancy of measurements, reduced measurement noise, and better represent the region movements better than individual PMU measurements. |
| Resource Controller (RC) | Control units that receive the RA signals from around the system and process to provide triggering signals to its connected resource(s). An RC is associated with a region, and there can be several RCs in a region. It sends the trigger to the control interface at the plant through hardwired signals or a fast protocol such as IEC 61850 GOOSE. |
| Control Interface to plant | Plant control system that receives the trigger and translates it into actions. |

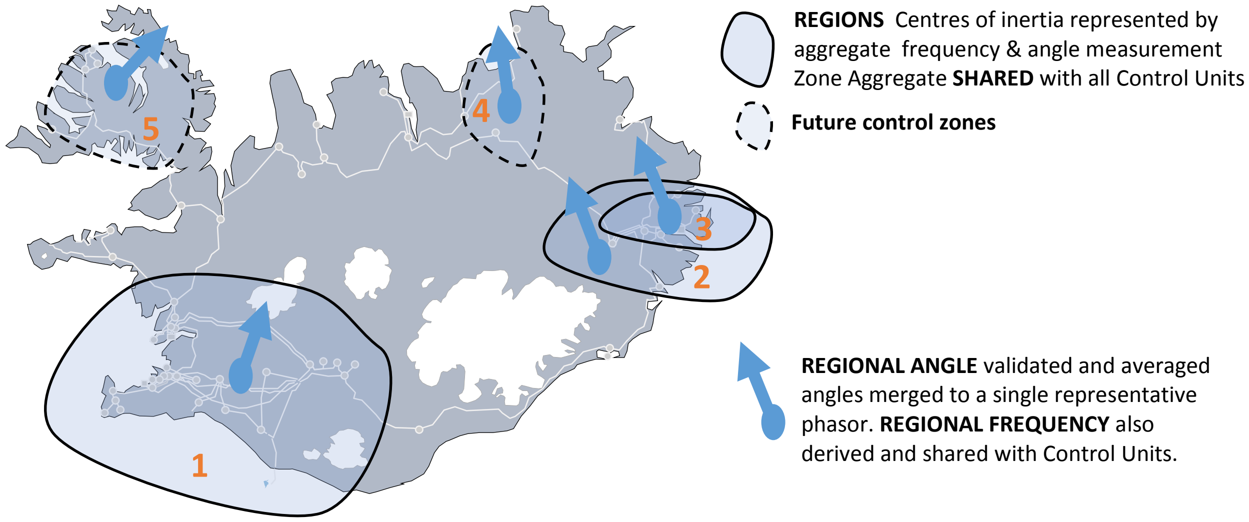


**Figure 4 Regional Aggregation of Frequency and Angles**

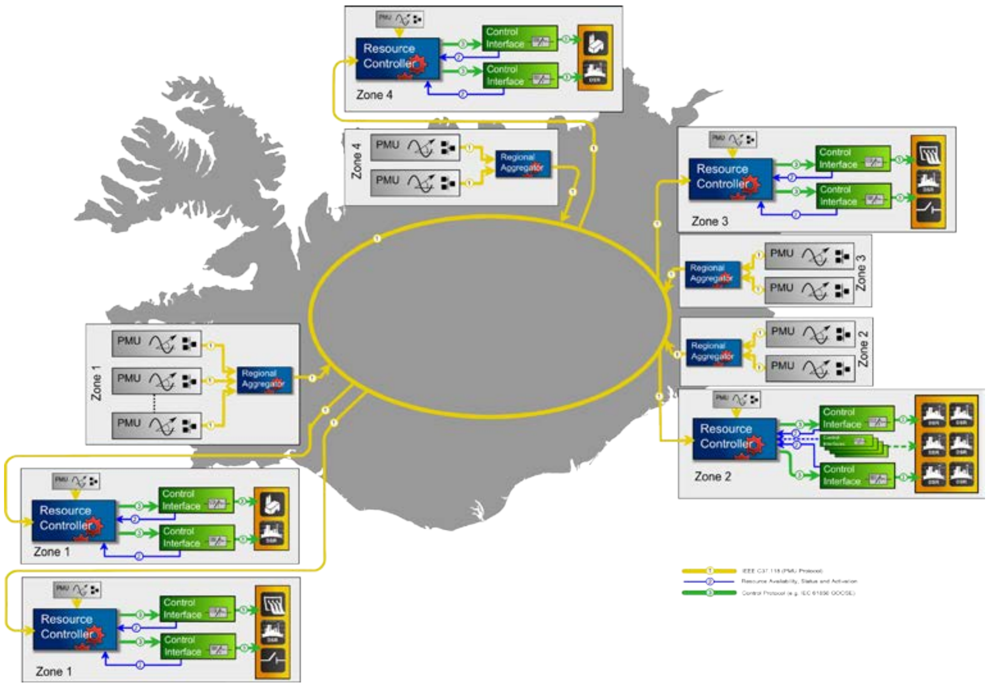


**Figure 5 Regional Aggregators (RAs) and Resource Controllers (RCs) in a distributed control scheme**

Figure 5 shows the intended architecture where the RAs share data with all RCs without going through a Phasor Data Concentrator (PDC). However, for the trials, a simpler initial architecture was used where data was sent from the control centre PhasorPoint™ Wide Area Monitoring System (WAMS) to units that act as RAs/RCs. This was done to introduce wide area control in incremental steps without impacting the WAMS infrastructure that is a critical part of the operational system observability. The performance in the trial is:

| | |
|---|---|
| 40ms | PMU latency, consistent with P-class latency in IEEE standard for synchrophasors [8] |
| 160ms | Network & PDC latency |
| >99.8% | Data availability (control availability much higher due to designed gap tolerance) |
| 20ms | Cycle time of PhasorController™ platform |
| 20-300ms | Algorithm latency, typically 20ms for digital trigger, 80ms severe ROCOF, 300ms marginal ROCOF event triggering |

Further delay time and data availability improvements are targeted through migration to the Figure 5 architecture, principally by avoiding use of a monitoring PDC and by enhancement of the event detection algorithm.

The process of determining the real-time triggering of the system is as follows:

1. Data quality checks are applied to incoming data to the RAs
2. Regional frequency and voltage phase angle signals are produced by RAs using several PMUs. These values are robust against loss or degradation of data from some of the PMUs.
3. RA frequency and angle signals are shared with RCs. Each RC belongs to a region, and applies the following process to the devices under its control:
    a. **Island detection.** Identify if the system is islanded using RA angle and frequency differences. The RC determines which regions are connected to its region.
    b. **System Aggregate values.** The RC produces a system frequency, system-ROCOF and system angle across all of the connected regions.
    c. **Event trigger.** The RC determines whether a high or low frequency event has occurred, principally by comparing system-ROCOF with thresholds, which are adapted depending on which regions are connected with the RC's area.
    d. **Location enabling.** Action is enabled or inhibited for a region depending on whether the angle from the RA in the relevant region is leading or lagging the system average. Load reduction and generation raising are enabled if the area angle is lagging and frequency is low and/or falling. Load increase and generation reduction are enabled in an area where the angle is leading and frequency is high and/or rising. Thus, angles are shifted towards the system mean by the control action.
    e. **Direct trigger.** Where appropriate, a very fast initial response can be obtained and used in nearby resources by triggering directly from a digital status value, e.g. smelter potline operating trip. Locational sensitivity must be respected.
    f. **Fast Ramp Duration.** In the case of Generation Fast Ramp, a triggering event will raise a signal to indicate that the RC is controlling the machine and a signal to command a generator ramp. The ramp signal stays high until the system need is satisfied, e.g. downwards ramp until frequency reaches 50.2Hz. Further constraints are applied, such as avoiding reverse power and rough running. Once the ramp is complete, a further settling is applied before the RC passes control back to the governor and the standard governor operating mode is resumed.
4. Each RC reports its calculations and digital status values into the WAMS system, and a real-time operational summary is provided to the control room operators, so that the operation can be supervised in the control centre.

## CHARACTERISTICS OF RESOURCES

The resources for fast control are categorized as discrete or ramping control, as defined in Table 1. The resources categorized as discrete control act rapidly to reduce the slope of the frequency. This leads to the change in gradient illustrated in Figure 6. Ramping responses use the same trigger to start the ramp, and are subject to the same locational enabling mechanism as discrete response, but it takes time to deploy. The trigger signal is held on as long as the ramping resource is needed. It can be beneficial for the ramping responses to continue beyond the zero frequency gradient since a hydro generator needs to ramp through a rough-running zone, and because some fast-acting resources e.g. smelters must return to their original values. In the practical implementation, it was decided to stop the ramp-down when frequency returned within 50.2Hz.

In addition to the wide area controlled resources, there is fast response delivered from geothermal power stations, which can be very useful in containing frequency in the south west. The geothermal fast-valving response is short-duration, and turbines must return to their pre-event output rapidly, and much of the response needs to be replaced by hydro within about 6s. Another approach being investigated (but not yet trialled) is to adapt the line of splitting between network islands as they form, to improve the power balance in the resulting islands. The particular case investigated would choose which breaker to open such that two hydro units would connect to the East or the West islands.

| | Examples | Target Latency | Description |
|---|---|---|---|
| **Discrete control** | Smelter load step up or down (Nordural and ISAL)<br><br>Load trip<br>(East Iceland Industrial Load) | 0.5s | Response approximates a step in power, either by breaker opening or power electronic control.<br>The smelter control is an examples of controlled load steps and East Iceland Load Shed is breaker-tripped load shed. These are disctinct from conventional under/over-frequency tripping. |
| **Ramp control** | Generator fast-ramp<br>(HRA hydro generator)<br><br>Load ramp<br>(future potential) | 2-20s | Ramp control turns on within a target time of 0.5s and remains on until a power balance is achieved (SROCOF=0) or continued to avoid hydro rough running, or to pre-empt other short term fast response being restored. Down-ramping is trialled, but both directions could be used if available. |
| **Thermal fast-valving** | Geothermal governor fast-valving | 1-3s | Currently triggered locally when f>51Hz, power can reduce in about 2s to near-zero at all units. However, the turbine must restore power quickly, typically returning to half-power within about 6s and continuing to full power within about 1 min. |
| **Intelligent splitting** | Control decision between two breaker opening options to connect 2 hydro units to east or west islands. | <1.0 | If the system response to a disturbance shows that the system will separate into islands, the control scheme determines which breaker to open so that 2x 55MW hydro units connect to the eastern or western islands. |

**Table 1 Categorisation of wide area responses**

In the trials, the resource profile for discrete response by two smelters (Nordural and ISAL) is shown in Figure 6. There are two levels of upward power triggers (High Frequency) and two downward (Low Frequency) for both participating smelters. Figure 6 also shows measured response where the resource was activated.

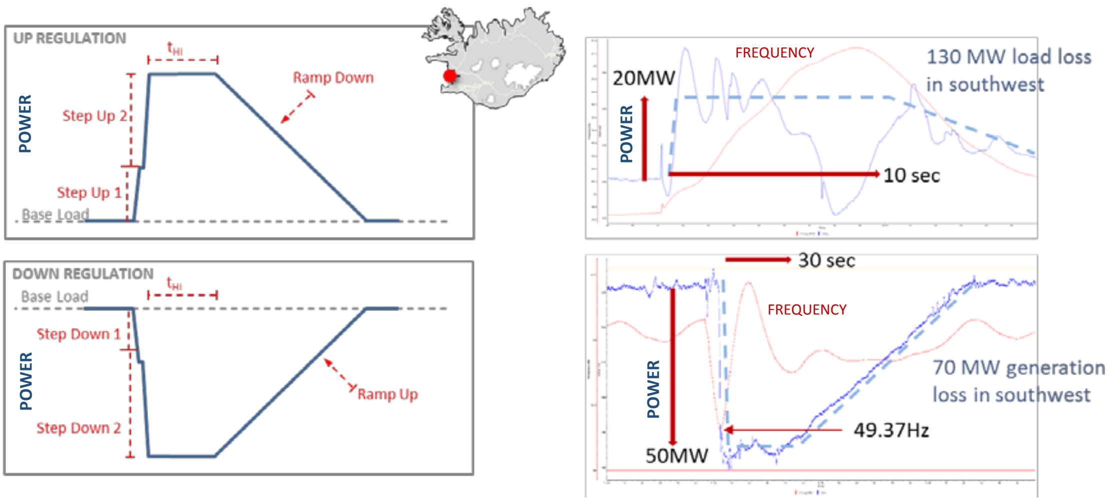


**Figure 6 Smelter response profiles and measured responses at Nordural**

Another discrete resource is load shedding in East Iceland. Six fish processing factories with a total maximum load capacity of 90MW are connected to a weak part of the 132kV network in East Iceland. The loads are tripped for disturbances in which the east area is enabled by the location function. Different triggering thresholds are applied for each controlled resource, to so that the response is proportionate to the event size. In one activation during an islanding event, the load shedding scheme delivered 32MW of load shed response in the island, acting to stabilise the frequency.

Ramping response is enabled at one 70MW unit at the Hrauneyjarfoss (HRA) hydro station, with new governor control functionality developed by Andritz. The interaction between the wide area control and the governor control is shown in a fast-ramp response to a real disturbance in Figure 7. A full downward load ramp is achieved in just 17s, much larger and faster than conventional response.

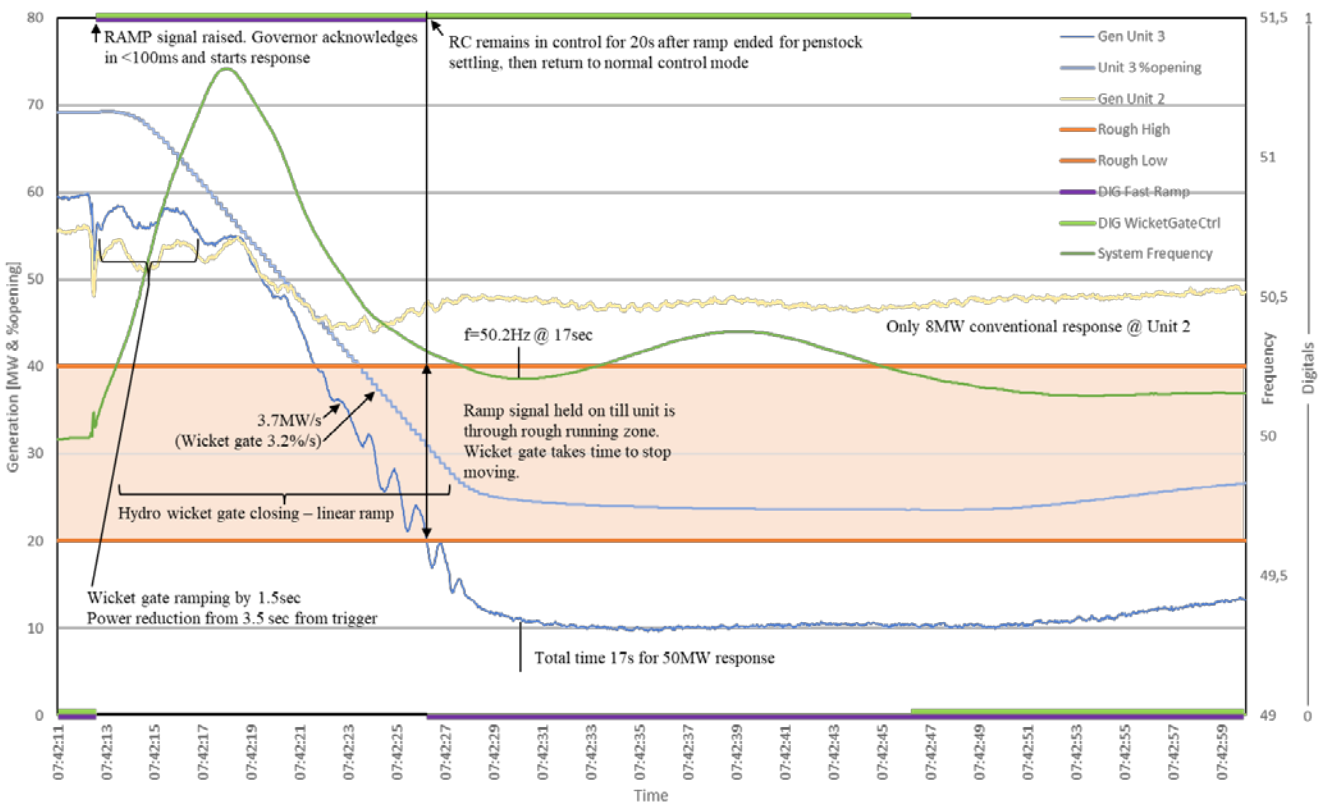


**Figure 7 Example of hydro governor fast ramp action in response to a grid disturbance**

The implementation of the HRA fast ramping approach required design and commissioning of a new governor software function that interacts with the wide area control system. It also includes its own layer of operational security to ensure that the unit operates within its design capability for boundaries such as reverse power, rough running (or “forbidden”) zone and ramp rate. It is important that there is a valid power setpoint when the control mode passes back to the normal operating mode. The co-ordination between systems is designed and tested to ensure that no situation can arise where the machine is in an indeterminate control state.

As well as co-ordination between wide area control and governing control, it is also important that the control centre’s Automatic Generation Control (AGC) is co-ordinated to ensure that the new operating point of the generator is recognised without the potential of AGC returning the unit to the pre-event power setpoint. A further security measure to be added is a feature to recognise the condition where wide area control data loss or equipment failure results in the machine remaining in the rough running zone, and control centre automation will move the operating point away from rough running.

## SYSTEM RESPONSE

The overall response profile of the non-conventional response in south western Iceland is shown in Figure 8 for the large load loss shown within the area. The event sequence is based on a real event, involving a large load loss followed by a second smaller load loss and a further load ramp, all within the southwest. The ideal power balancing response would be immediate, close to the volume tripped and sustained over time, so that there would be very little frequency and angle movement. Clearly, this is not practically achievable, and there will always be some frequency and angle movement due to imbalance and need for some longer-term conventional governing response. However, achieving performance as close as practical to the ideal response reduces the impact of the disturbance.

The profile of non-conventional response is shown with the existing capability that is now active in the southwestern part of the system. There is clearly a value in rolling out the capability to further units to improve frequency containment in the area, however the trials already show the value of the control applied.

From Figure 8, it may be observed that:

- The thyristor-controlled smelter load ramp is the fastest initial response in the southwest, addressing the dynamic angle swing and reducing the frequency peak. The control is implemented in both southwest smelters, but the capability of one may be lost by a trip.
- The geothermal governor fast-valving response by units in the southwest is very useful for containing the frequency. There are potential improvements in starting the response earlier for a close disturbance (before 51Hz is reached) with wide area control, and delayed for a distant disturbance.
- The geothermal response is short-term and must be replaced.
- Hydro fast ramping response is sustained and replaces the time-limited responses. Applying this in more units would improve the overall frequency behaviour.
- The load tripping resources are all in the East; the action can be fast and sustained, but is also disruptive for the customer and used only when essential.

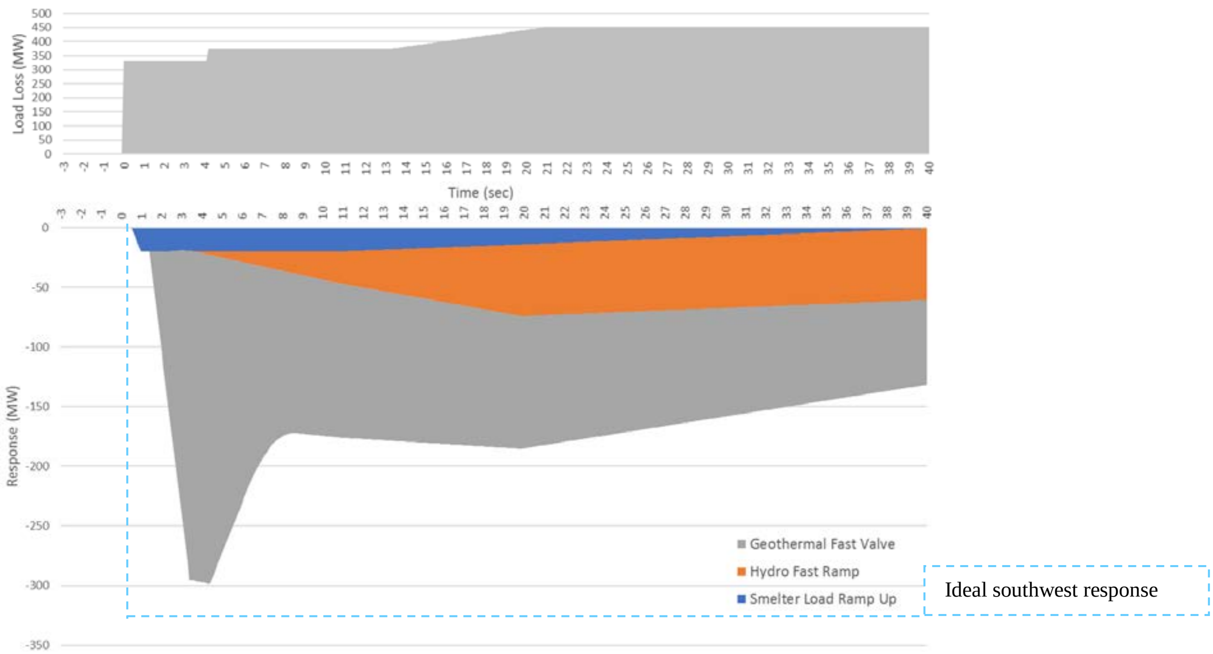


**Figure 8 Expected non-conventional power response contributions to western load loss balancing**

## RELATIVE TECHNICAL VALUE OF FREQUENCY AND STABILITY SERVICES

In common with other TSOs addressing the issue of low inertia and fast response, there is a need to encourage flexible responses. The responses described in this paper show different profiles, but the control approach enables them to be co-ordinated to achieve an overall predictable and effective response profile for each area. There are considerable cost savings to be achieved in using existing plants to manage the frequency and stability performance rather than using dedicated resources such as battery storage. To use existing resources, it is necessary to account for inherent variability in responses arising from the technical capabilities of different plants and the operating state defined by the plants' primary roles.

In the Icelandic situation, it is recognised that there is mutual benefit to generation, demand and network stakeholders to improve frequency and stability management, influencing the security of supply and cost of ancillary services as well as the stress and performance of plant. Also, there is an environmental benefit in using the existing network infrastructure more intensively, increasing the available connection capacity while keeping network reinforcement to a minimum. There is further work to be done in the area of value and incentives in order to roll out more rapid response capability, but this is done in the context of consensus across stakeholders that there is a shared value in applying the approach more widely.

As a step towards defining flexible response services, it is important to recognise the relative values of response to the grid, accounting for their contribution to containing frequency and preventing or mitigating islanding. Timing, location, volume of energy delivered and ability to sustain a response are important factors. Also, the frequency with which a response may be called on may vary, for example, load or generator tripping may be the fastest and most sustained response but as it is the least desirable for the primary function of the plant, it would be a 'last resort' reserved for the most severe disturbances.

Figure 9 illustrates the different stages of a disturbance. Immediately following protection operation, there is a dynamic angle swing, where angles will diverge typically for about 1-2 seconds. The angles will swing back together or the system will island. As illustrated in Figure 3, the frequency continues to rise until there is a balance between generation and load and the frequency gradient becomes zero. The frequency will return towards 50Hz, but will not reach it by primary control alone. Secondary mechanisms of Automatic Generation Control (AGC) and operator dispatch will restore the system to its nominal frequency.

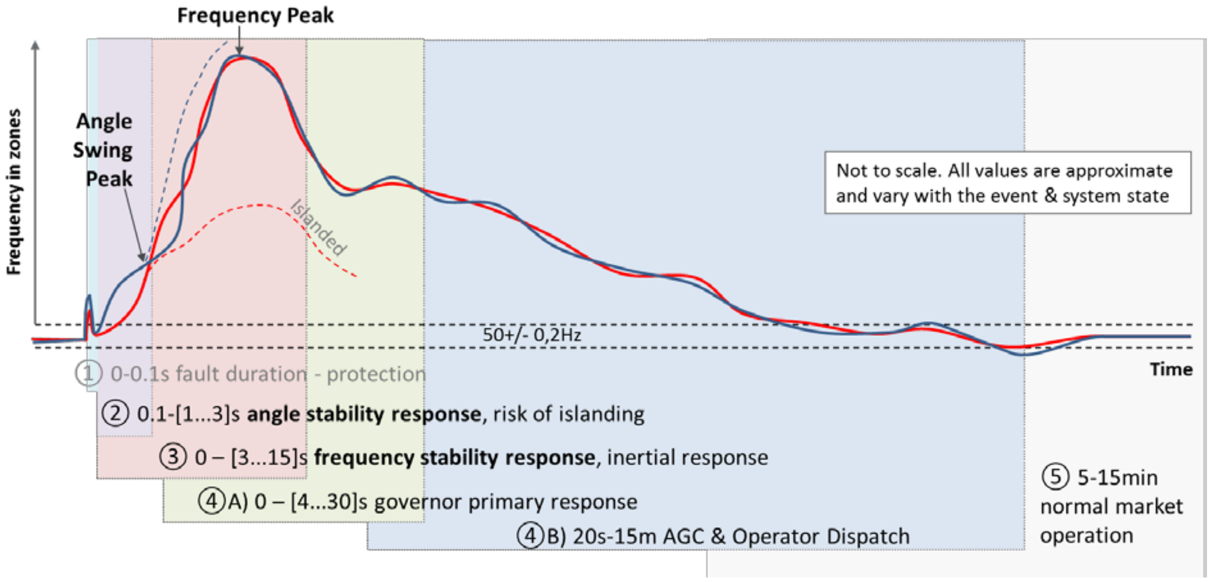


**Figure 9 Typical stages of response to a disturbance**

Conventional services of governor-frequency regulation (ie droop control) and spinning reserve address 4A, typically starting to deploy at 3-4 seconds for hydro units and continuing up to about 20-30s. However, the conventional response has very limited capability to address stages 2 (Angle Stability) and 3 (Frequency Stability) because of the shorter timeframes. Without fast response capability, there is a risk of further loss of generation and load due to islanding and local frequency protection of plant. Services are needed to contribute to stages 2 and 3, but depending on the technical characteristics, they may also be able to contribute to stages 4A&B. Therefore, the duty for the full range of stabilisation services can be shared across generation and load.

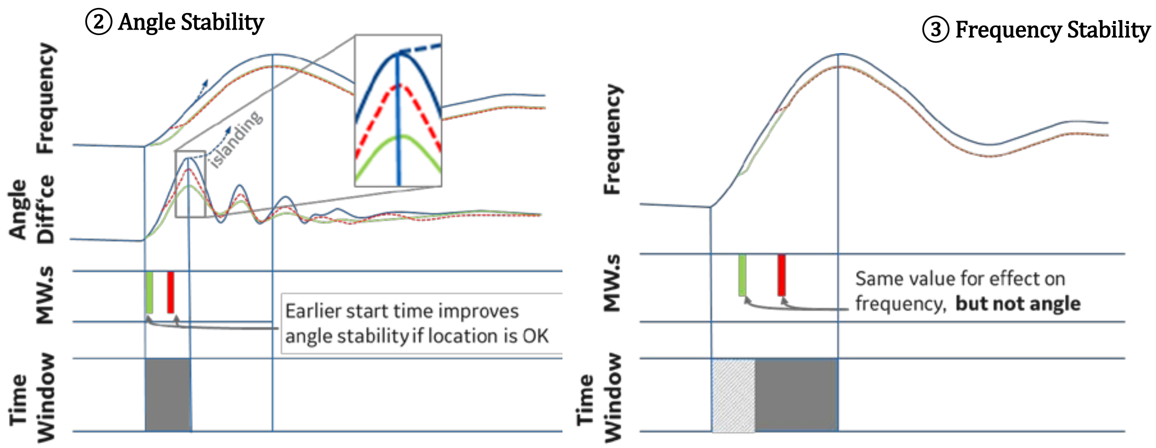


**Figure 10 Relative value of energy delivery in Stages 2-Angle Stability and 3-Frequency Stability**

Figure 10 illustrates the relative value of energy supplied at different stages in a disturbance. The value of a 1MW.s energy response delivery indicated by the green and red injections is equal in terms of frequency stability as long as it is delivered between the disturbance and the frequency peak. Thus, the green and red injections of energy response have the same effect on the frequency peak although they occur at different times. Clearly, a response that is intended to deliver a frequency stability service can generally deliver a greater response if it starts as early as possible. However, a frequency stability response delivered in the wrong location during the angle swing period has no value, or even negative value as it increases islanding risk and may degrade the balance in the islands if separation occurs. By contrast, the value of 1MW.s response to angle stability has a higher value if delivered early, and the value diminishes up to the point of the angle swing peak. There is only a value if the response in the angle swing is location sensitive, otherwise it may degrade the angle stability.

The technical value of the response therefore suggests a time-dependent value profile as illustrated in the top chart of Figure 11. There is additional value to location-sensitive services that can respond within the first angle swing (ie within about 3s) and also in services that respond before the frequency peak (ie within about 4-7s).

Figure 11 shows the response profile of an example participant, and the estimated value of the response. Responses that can provide the early stage response should be encouraged to do so, while those that cannot act quickly can still derive value for a longer-term response.

Further work would be required if there is a need to quantify the relative values of the time segments, and to determine the volume of responses required for system operation for each area.

Landsnet has a strong interest in probabilistic security assessment, and demonstrated a novel on-line security assessment toolset in the EU GARPUR project [9,10]. Using the methodology, it is possible to assess the probability and impact of outages with and without smart grid technologies. While the approach currently has an emphasis on steady state loading, there is an interest in the approach to dynamic issues, with the aim of quantifying the benefits of risk reduction due to fast response capability.

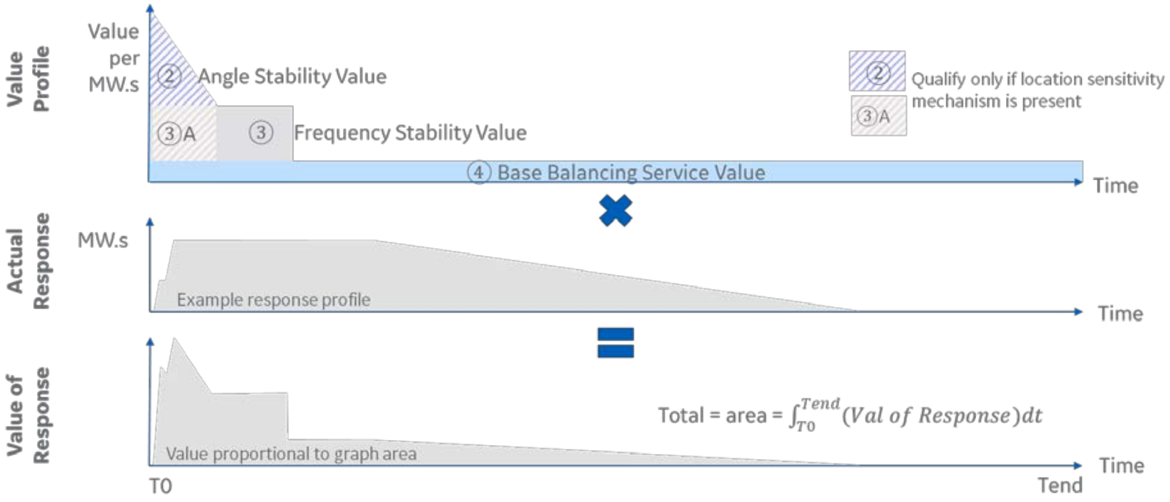


**Figure 11 Illustrative response value profile for stages of disturbance response**

## CONCLUSION

The technical demonstration proves that a fast, locational response to grid disturbances is possible, and that it can be achieved with a distributed control approach using synchrophasor measurements. The control approach is designed to utilize various different response technologies, both load and generation, to provide a coordinated response without adding new power equipment.

The benefits include:

1. Reducing the occurrence of islanding and the consequent risks and losses of generation and load.
2. If islanding does occur, it improves the likelihood of the islands surviving, as there is an improved balance in the islands as they form.
3. Reducing the risk of load or generation loss through extreme frequency deviation.
4. Increased efficiency in delivering frequency response services by opening the service to many more participants, without incurring the cost of installing dedicated devices.
5. Resources can be used that connect at any voltage level, including transmission and distribution levels.
6. Reduced stress on machines that are involved in frequency control:
    a. Reducing mechanical stress from large speed excursions during disturbances
    b. Reducing the time of operation within the rough running zone
    c. Reducing continuous frequency control action; separating large-disturbance response from small-disturbance provides scope for reducing oscillations.
7. Increased transfer capability of the network, as a result of actions that reduce angle separations.

Iceland's experience of operating a system with low inertia is valuable for other systems where there is low or reducing inertia. It is also relevant for larger interconnections where parts of the system have low inertia and where there are transmission boundary constraints. The novel technical approach leads to the opportunity to contribute services that combine angle stability, frequency stability and balancing, provided by any grid users who have a useful response capability to offer.

It is envisaged that more resources will be added to the wide area control system using the mechanisms described as templates for new additions to the scheme. An extension to include geothermal fast-valving within the wide area control scheme would be valuable at the geothermal plants.  Future work is also planned on the networking architecture to further improve latency and availability of the wide area control system as the operational dependence on the system increases. It is also intended that the work on intelligent network splitting should be generalized and applied to other areas of the grid where there is a risk of islanding, particularly as new generation is added to the weak network in the north.

## ACKNOWLEDGEMENTS

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