Untapped Opportunities for Grid Reliability Improvement

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Abstract

Hydropower generation has been shown to provide the most substantial component of Primary Frequency Control of any generation type in the Western Electricity Coordinating Council (WECC) [1]. Primary Frequency Control is an important component of grid reliability and as such is regulated by the North American Electric Reliability Corporation (NERC). This paper explores the untapped potential for increasing hydro's role in improving grid reliability via Primary Frequency Control by adding or maintaining governor systems at smaller plants. Approximately two-thirds of the hydro-turbines in North America are below 10 MW and are not subject to NERC Primary Frequency Control regulations. Primary Frequency Control support is voluntary for owners and operators of these power plants. This paper will discuss the various practical considerations and examine the costs and benefits of maintenance or modernization of these smaller hydro-turbines to increase hydropower's contribution to grid stability. A wide range of aspects will be considered; not only direct costs and benefits, but indirect costs and benefits as well, such as the opportunity costs of finding substitute capacity in energy markets or balancing authorities.

Grid Stability and Frequency Response

"System frequency is a continuously changing variable that is determined and controlled by the second-by-second (real time) balance between system demand and total generation. If demand is greater than generation, the frequency falls while if generation is greater than demand, the frequency rises" (www.nationalgrid.com). Frequency response on an electrical network is a measure of "how well the system responds to a sudden loss of generation, one of the most important threats to reliability" (Eto, et al., 2010). There has been a gradual decline of stability on the grid (Martinez, Xue, and Martinez, 2010) as shown in Figure 1, where the y-axis is:

$$\text{Frequency Response} = \frac{\text{MW Imbalance}}{10 \cdot \Delta\text{Frequency}} \quad \left(\frac{\text{MW}}{0.1\text{Hz}}\right)$$

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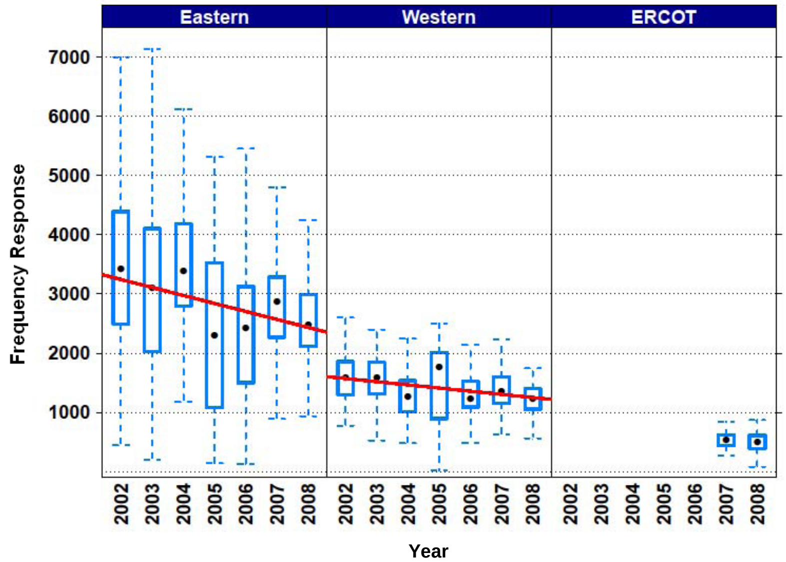

Figure 1: Yearly Trends in the Frequency Response of the Eastern, Western and ERCOT Interconnections. Source: (Martinez, Xue, & Martinez, 2010)

There are three foundations of grid frequency stabilization including Primary, Secondary and Tertiary Frequency Control, shown in Figure 2.

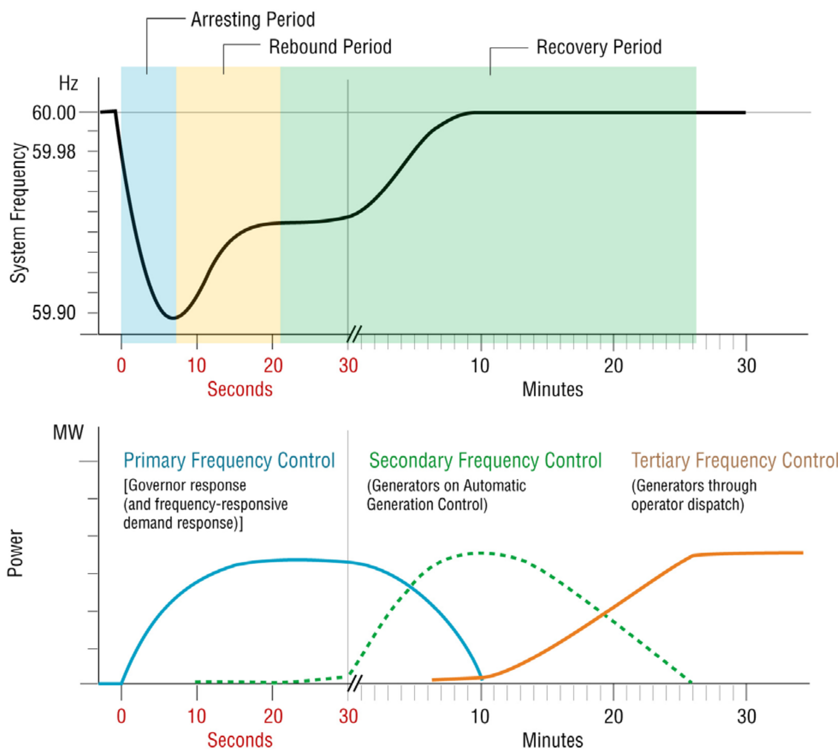

Figure 2: Sequence of Dominant Action by Primary, Secondary, and Tertiary Frequency response. Source: (Eto, et al., 2010)

Primary Frequency Control types of generation are categorized in Table 1.

Category	Attributes	Generation Type
Must-take	Dependent on variable resource. Requires additional generation capacity.	• Solar without storage • Wind
Peak Load	Provides power during peak demand. Ramps up and down quickly. Dispatched using Automatic Generation Control when a spinning reserve or Operator Dispatch if a non-spinning reserve.	• Natural gas combustion turbine • Solar(coincides w/ summer peak season)
Intermediate Load / Load Following	Varies production to follow demand. Predictable availability. Primary Frequency Control.	• Natural gas combined cycle • Solar with storage[2] • Hydropower
Base Load	Low fuel and operating costs Constant rate of production. Often very large to benefit from economy of scale	• Coal • Nuclear • Biomass • Geothermal • Hydropower

Table 1: Categories and Attributes of Different Generation Types. Source: (Turchi, 2010)

Hydro Generation and Primary Frequency Control

Primary Frequency Control is dominant from milliseconds to minutes after a frequency excursion. Primary Frequency Control is the result of automatic control (typically governing) of synchronous generation sources. Primary Frequency Control immediately opposes frequency deviations without higher level intervention through supervisory control such as SCADA systems or Operator action. This is currently an active area under investigation by NERC as published in the Frequency Response Initiative (Cummings, 2010). This initiative emphasizes the importance of Primary Frequency Control and provides data indicating that this is a major factor to the recent decline in grid stability (Aswani, Clarke-Johnson and Runyan, HydroVision 2011).

Based on conclusions obtained from, “The Impact of Hydroelectric Power and Other Forms of Generation on Grid Frequency Stability for the WECC Region” (Aswani, Clarke-Johnson and Runyan, HydroVision 2011), hydropower and gas turbine power plants contribute the greatest share of Primary Frequency Response during grid frequency excursions. See Figures 3 and 4. Steam plants powered by coal, gas, or nuclear fuels and combined cycle gas plants contribute a smaller percentage of Primary Frequency Response. Wind and Solar power are “Must-Take” forms of power generation that make no measurable contribution to Primary Frequency Response. Variations in power supplied from wind and solar must be compensated for by other sources of generation. These variations could also magnify grid instability (adapted from Turchi, 2010).

[2] This is an emerging technology that has not been widely implemented at the utility scale.

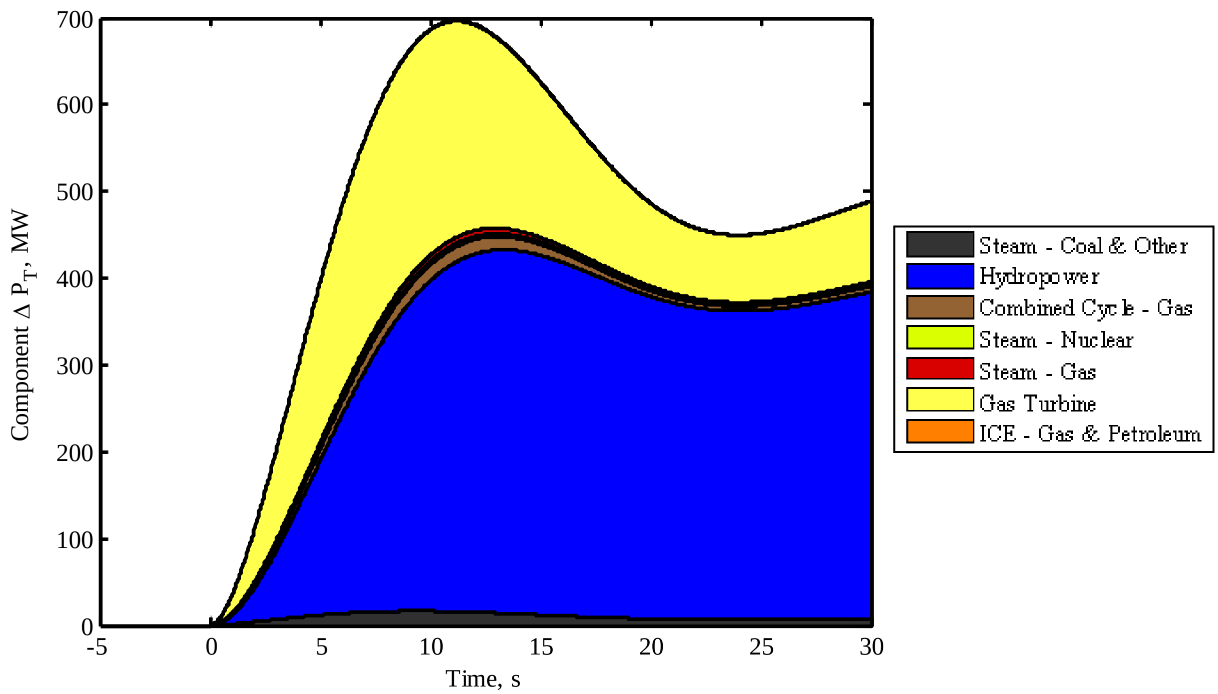

Figure 3: Simulated Power Contribution by Generation Type after a Power Generation Dropout of 500 MW on WECC, *X* = 33%

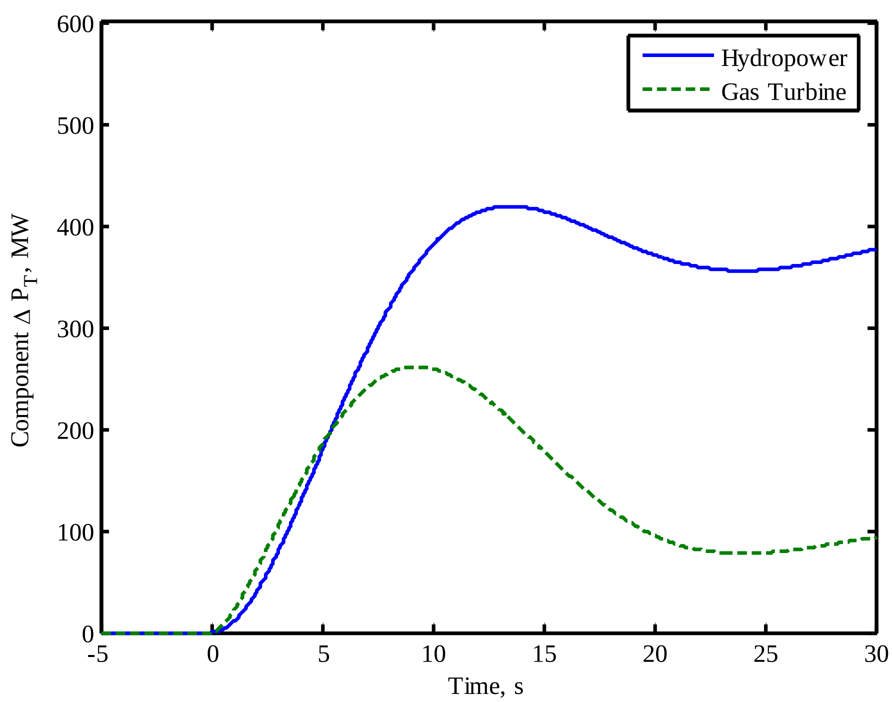

Figure 4: Power Contribution from Hydropower and Gas Turbines after a Power Generation Dropout of 500 MW on WECC, *X*=33%

Estimates for the WECC grid as a whole in 2008 showed hydropower generation contributed between 25-90% of the Primary Frequency Control response in the first 10 seconds after an under-frequency event and before intervention from Automatic Generation Control. This value is dependent on the percentage of gas turbine generation available as frequency responsive capacity. See Figure 5. Assuming that about 33% of gas turbine capacity was available online and as frequency responsive capacity (*X*=33%), then hydroelectric generation contributes approximately 55% of the Primary Frequency Response at 10 seconds after a power dropout event (Aswani, Clarke-Johnson and Runyan, HydroVision 2011).

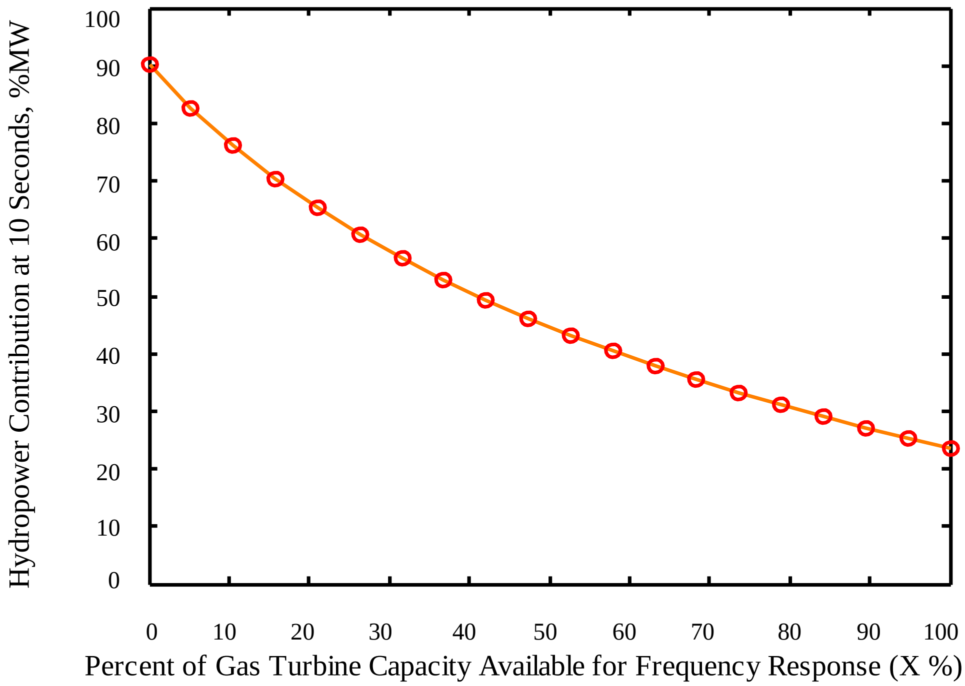

Figure 5: Percent of Primary Frequency Control Response from Hydropower at 10 seconds after a Power Generation Dropout of 500 MW, Sweep of *X* Values

Hydro Governor Operation

In order to provide the greatest contribution to Primary Frequency Control, governors controlling hydropower turbine/generator units must be maintained properly, and must control with a Speed Droop response. The manner in which these units are operated must also be factored in when determining the impact a unit can have on Primary Frequency Control of the grid. Going forward, the discussion will focus predominantly on mechanical and analog type governors, but bear in mind that all governor systems can be affected similarly.

Units are considered “block-loaded” when they are connected to the grid and their Speed Adjust setting is fully increased to its maximum, and the unit is operated on an adjustable Gate Limit somewhere between the speed-no-load position and 100% wicket gate position. In this so-called block-loaded mode of operation, the governor is unable to regulate frequency because the Speed Adjustment has been saturated, or because the unit is operated at the maximum servomotor position.

Either of these conditions will dramatically limit the governor's ability to react to grid frequency disturbances. It is physically impossible for a block-loaded unit, or a unit operating at 100% wicket gate position, to accept additional load when grid frequency drops slightly. Although it is possible for a block-loaded unit *not* being operated at 100% gate position to shed load if needed, this unit will have a delayed reaction, or if the speed/load adjustment is saturated firmly enough against a servo limit and the amplitude of grid frequency change is less than that saturated amount, the unit may not react at all to help stabilize a decreased demand on the grid.

"Headroom" is the readily available capacity of a unit or system. In order for a system to react most effectively to increases in load demand, enough total headroom must be available for the units in that system to respond to the increase in load demand, prior to exhausting available headroom. Block loaded units have no headroom. Regarding Primary Frequency Control, it has been observed that headroom only matters when it becomes scarce. (adapted from GE Energy Consulting Report by Miller, Shao, Venkataraman, 2011).

Hydro Governor Maintenance

Friction and lost motion in a governor system are the two greatest contributors to unit instability and are symptoms of a governor that is either misadjusted or in need of maintenance. These problems are easily identified and eliminated, or at least greatly reduced, during proper planned maintenance by suitably-trained technicians.

Governors that do not receive proper maintenance at the recommended interval will eventually degrade to the point where block-loading or Gate-Limited control is the only satisfactory control mode available. Not only will improperly maintained or unmaintained governors react poorly to varying unit speed or load demands, they make the unit very difficult to synchronize and load accurately. These governors are frequently operated as servomotor positioners that require external input to correct for sustained grid deviations, and consequently provide no Primary Frequency Control. Instead, they are used exclusively for Secondary and Tertiary Frequency Control unless already at 100% servomotor position.

When these governors are used to control frequency or load via Speed Adjust setpoint changes (and thus not "block-loaded") they typically cannot respond to loading variations on the grid without hunting, as they are unable to react suitably due to worn parts causing lost motion and friction. In fact, hunting is the most obvious indication of a governor in need of an overhaul.

Another important side effect to note about a poorly-maintained governor is that the adapted operational practice (the block-loaded and Gate-Limited control modes) to attempt to operate them effectively only accelerates the mechanical degradation of the worn parts. As mentioned, the lack of maintenance of a governor typically leads to them being operated as a positioner, rather than a true governor. When operated on gate/servo limit or loaded solidly against the 100% servo position with an over-biased Speed Adjust increase signal, the vibration that is designed and implemented into the governor to oscillate, or "dither", the governor's control valves (pilot and relay/distributing) is not transmitted to the hydraulic system. Rather, it is absorbed within the mechanical links and levers of the governor, which causes excessive wear to linkage pivot and component contact points over time. This increased wear sustains the "snowballing" effect of accelerated wear, poor controllability, and excessive unit hunting resulting in even less contribution to Primary Frequency Control.

Hydro Governor Tuning

Just as significant as an appropriately-maintained governor is to the stability of a hydro generating unit is the proper tuning of that governor. Two factors must be tuned on the governor system; Permanent and Temporary compensation. There are regulations for permanent compensation (Speed Droop) on units over 10 MW. However, there are only recommendations for temporary compensation. Permanent compensation (Speed Droop) determines the magnitude of the response to a frequency excursion, while temporary compensation determines the rate in which the unit will respond (Kroner & Bérubé, 2008). Appropriate maintenance and periodic overhauls will also allow the governor to be properly tuned for optimal response, both on-line and off-line.

Increasing Grid Stability with Additional Hydro Governors

Approximately two-thirds of the hydro-turbines in North America are below 10 MW and are currently not subject to NERC Primary Frequency Control regulations. Support of Primary Frequency Control is entirely voluntary for owners and operators of these hydro-turbines.

We explored how much stability could be added to the grid if hydro units with outputs lower than 10 MW were included in NERC's Primary Frequency Control regulation. Estimates show that for every 1% of hydro generation added as frequency responsive capacity, there is approximately 0.5% improvement in grid Primary Frequency Control (Gas Turbine *X*=33%) for WECC (Aswani, Clarke-Johnson and Runyan, Hydrovision 2011).

There are nearly 1500 known "Small Hydro" units in North America, each with an output of 2 MW or greater, but less than 10 MW. NERC evidently believes these units are unnecessary to support Primary Frequency Control. However, the total output of these individual units is approximately 6,850 MW. That "combined unit" is not so "small" anymore.

When 6,850 MW is added into the total hydro generation on the grid, currently estimated at around 160,000 MW, that could provide an additional 4% capacity to the Frequency Responsive grid capacity, or slightly more than 2% improvement in Primary Frequency Control of the grid overall. If all of these small units contributed to Primary Frequency Control, a power demand on the grid that would currently decrease the frequency by 0.500 Hz could be improved by 0.012 Hz. NERC would realize a diminished frequency excursion that is arrested at 59.512 Hz instead of allowing frequency to decrease further to 59.500 Hz. Although this may not appear to be much of an improvement, it could in reality be enough to avoid reaching Under Frequency Load Shedding (UFLS) thresholds for power transmission owners and operators, preventing tripping-off larger swaths of generation capacity and initiating or intensifying a cascading brownout or blackout. This improvement, combined with properly maintained and operated governors on all units with outputs of 2 MW and greater, would diminish present grid frequency excursions even further.

Governor Maintenance Costs/Benefits

Typical costs for preventive maintenance of a common Woodward Mechanical Governor (Gateshaft or Mechanical Cabinet Actuator) averages approximately $8,000.00 to $14,000.00. The maintenance performed consists of minor overhaul, including typical replacement parts, and re-tuning of the governor for optimal on and off-line response.

Preventative maintenance of the governor system results in direct benefits that can be realized almost instantaneously by the owners and operators of the associated units. Increased off-line stability greatly reduces the time required to synchronize the turbine/generator to the grid, so the units spend more time generating. After connecting to the grid, more precise control of generator frequency and kW/MW output is also achieved. Governors that control properly demand less support and involvement by Operations when synchronizing and loading or un-loading units.

Governor Retrofit/Upgrade Costs/Benefits

Typical cost to upgrade one Woodward Gateshaft Governor to a Digital (PLC) Control system can range from $50,000.00 to $150,000.00. The complexity of the operating system and the number of Input/Outputs (I/O) the system requires makes the most difference in the final cost.

Benefits of upgrade to the owner utility primarily revolve around reduced maintenance and an improved Unit Controller interface. Rather than utilizing additional accessory governor hardware (e.g. Bodine motors) to communicate setpoints and other operational adjustments to a mechanical/analog governor, the new digital governor PLC can be just another node on a communication network. Precise and timely control of the unit is also greatly enhanced via the ability to remotely transmit "go-to" setpoints (speed, load, servomotor position, flow, etc.) directly into the governor PLC.

Additional Benefits of Governor Maintenance

Governors that are not maintained characteristically experience issues with bearing and component failures, linkage and pivot point friction caused by lack of proper lubrication, misalignment from wear or possibly lost motion initiated by excessive wear. Any of these symptoms can cause unplanned unit down-time. Oftentimes these unplanned outages are extended due to further deficiencies caused by lack of maintenance that are problematic to identify and troubleshoot effectively before returning the unit to operation in a timely manner.

Governors maintained in good condition typically do not require much more attention than recommended and planned routine maintenance to keep them operating correctly. Weekly and monthly checklist completion for inspecting and lubricating pivot points, adjusting oil levels, verifying hydraulic system operation, etc. are simple and routine to ensure the governor system continues to function at its peak.

In addition, more precisely controlled units can be operated in their most efficient working servomotor position to take full advantage of available water. Governor maintenance leads to accurate control allowing generation to be maximized on units that have a declining power output at, or past, certain servomotor positions.

More accurate control of units also enables for the participation of the unit in downstream flow control as well as the emerging Ancillary Services markets. Precise control of water flow has become a commodity in some areas that, at times, can bring more revenue than the total maximum generation output of those same units controlling the water flow. Correctly controlled units could also be incorporated in Ancillary Services, outlined in Figure 6, providing regulation or spinning/non-spinning reserve where units could deliver increased profits to their owners as a result of improved controllability, availability and headroom which allow these units to absorb or add real power into the grid, reacting to changing load demands quickly and accurately.

Figure 6: Examples of Ancillary Services (adapted from Kirby, 2006)

Service	Response Time	Duration	Cycle Time
Regulating	Online resources that can respond immediately to system-operator requests for up and down movements		
	~1 minute	Minutes	Minutes
Spinning Reserve	Online generation, synchronized to the grid, that can increase output immediately in response to a major generator or transmission outage and can reach full output within 10 minutes		
	Seconds to <10 minutes	10-120 minutes	Hours to Days
Non-Spinning Reserve	Same as spinning but does not need to respond immediately; can be offline but must still be capable of reaching full output within 10 minutes		
	<10 minutes	10-120 minutes	Hours to Days
Replacement/ Supplemental Reserve	Begins responding in 30-60 minutes; used to restore spinning and non-spinning reserve to pre-contingency status		
	<30 minutes	2 hours	Hours to Days

Conclusions

Because hydro generation contributes a large share of the Primary Frequency Control it is very beneficial to increase the number of hydro units that are contributing to the frequency responsive capacity to the grid.

Adding in the capacity of smaller hydro units (outputs 2 MW or greater, but less than 10 MW), available on-line with a droop response provided by a suitable governor system, noticeably increases a system's capability to react positively to varied load on the grid. Governed small hydro input can offset some of the need for power transmission owners and operators to shed load in support of grid frequency during increased load demand events.

Proper maintenance of governor systems controlling all sized hydropower units not only supports proper unit operation but it delivers a governor capable of precise and correct operation which is a critical requirement for optimizing Primary Frequency Control of the grid.

Environmental awareness and the accompanying "green power" effort will maintain the development of existing and additional sources of renewable energy (wind, solar, geothermal, and wave/tidal) that are inherently intermittent due to varying environmental conditions. Technological developments in the control and storage of renewable energy could enable increased reliability and a more stable input to the grid in the future, however; until then hydropower will continue performing the majority of Primary Frequency Control, and increasing the number of hydro governors that are properly operating in Droop will enhance the grid's capability to automatically respond to frequency fluctuations.

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