The Impact of Hydroelectric Power and Other Forms of Generation on Grid Frequency Stability for the WECC Region

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Abstract

With the increased use of variable forms of generation such as wind and solar, there is increased concern not only about load matching, but grid stability itself. Hydropower plants often are proposed to back-up variable sources due to the ability of hydropower plants to store their fuel/energy. In addition to compensating for the hourly and daily variations in output from wind farms and solar plants, hydropower plants can also make significant contributions to grid stability through the capabilities of their governing systems. Other conventional forms of generation may not be making the same contribution to grid stability due to the fuel efficiency, pollution reduction, block loading and/or other operating restrictions implemented in their control systems. This paper will present the results of an analysis of recent government reports and an investigation into the control methods used by various forms of generation. This paper uses some of the concepts and models presented in (Undrill, 2010).

Sources of Grid Frequency Stabilization

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 grid stability on the grid (Martinez, Xue, & Martinez, 2010) as shown in Figure 1, where the y-axis is:

$$\text{Frequency Response} = -\frac{\text{MW Imbalance}}{10 \cdot \Delta\text{Frequency}} \quad \left(\frac{\text{MW}}{0.1\text{Hz}}\right) \qquad (1)$$

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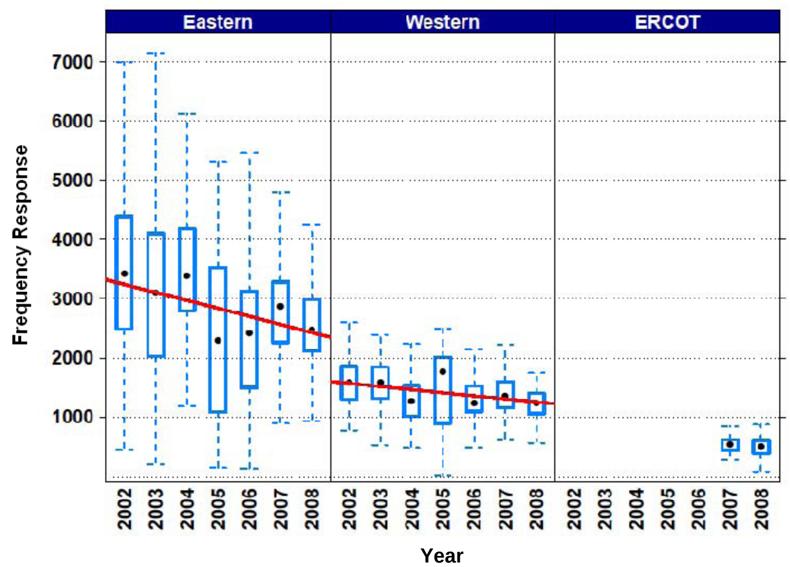

Figure 1: Yearly Trends in the Frequency Response of the Eastern, Western and ERCOT Interconnections. Source: (Martinez, Xue, & Martinez, 2010)

There are several sources of grid frequency stabilization including Primary Frequency Control, Secondary Frequency Control, and Tertiary Generation Control.

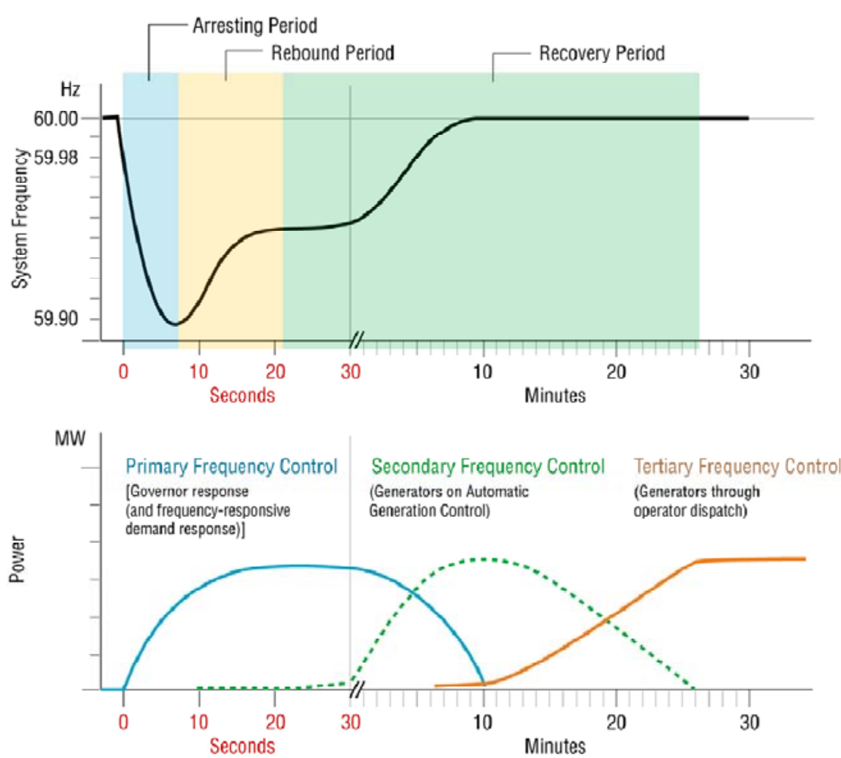

Figure 2: Sequence of Dominant Action by Primary, Secondary, and Tertiary Frequency response. Source: (Eto, et al., 2010)

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 recent 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.

Secondary Frequency Control

Secondary Frequency Control, also known as Automatic Generation Control, manages the allocation of loading among the available power plants. Its action follows Primary Frequency Control and takes place in the time scale of minutes (Cummings, 2010). Automatic Generation Control typically adjusts utilization of load following generation.

Tertiary Generation Control

Tertiary Generation Control is dominant in the range of minutes to hours after a frequency excursion (Cummings, 2010), and is usually a scheduled event in anticipation of expected load changes. Tertiary Generation Control adjusts the loading of turbines through operator dispatch. Utility companies make economic decisions for resource utilization and energy exchange through energy markets operated by an Independent Service Operator (ISO) or Regional Transmission Organization (RTO). Tertiary Generation Control typically involves decisions on start or stop of reserve generation capacity - that is Peak Load Generation.

Primary Frequency Control by Common Generation Types

Category	Attributes	Common Generation Type
Must-take	Dependent on variable resource. Requires additional system reserve generation capacity.	• Solar – Photovoltaic (P.V.) & Thermal • Wind
Peak Load	Provides power during peak demand. Ramps up and down quickly. Dispatched using Automatic Generation Control when a frequency responsive or Operator Dispatch if a non-frequency responsive.	• Gas Turbine (Typ. Aeroderivative) • Pumped Storage Hydropower • Internal Combustion Engine – Gas & Petroleum • Battery Storage (Future)
Load Following	Varies production to follow demand. Predictable availability. Primary Frequency Control.	• Gas Turbine (Typ. Large Simple Cycle) • Conventional Hydropower • Pumped Storage Hydropower
Base Load	Low fuel and operating costs. Constant rate of production. Often very large to benefit from economy of scale	• Steam – Coal • Steam – Nuclear • Steam – Gas • Steam – Biomass • Steam – Geothermal • Combined Cycle – Gas • Internal Combustion Engine – Gas & Petroleum • Conventional Hydropower

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

Steam – Coal

Steam coal power plants are attractive because of the low cost of coal fuel. Economic and emission factors are the most significant consideration for the base operating point of coal power plants. Large coal plants are often run at maximum output, peak efficiency, or other load constrained modes while following emission permits derived from regulatory actions driven by the Clean Air Act. Peak efficiency can be achieved through a combination of one or more of: control on boiler temperature, control on boiler pressure, and holding the steam valves at 100% to minimize throttling losses. Other load constraints for coal power plants may sometimes be present due to coal mill scheduling or use of scrubbers. When running in maximum output, peak efficiency, or other load constrained modes, the control response is limited. Over a large range of operation, coal power plants can change power output relatively slowly. For a large change in output ranges, the rate of change typically varies from 1% - 5% per minute (Rech, Rupp, & Wendelberger, 2008), (Global Energy Concepts, 2005), (Vuorinen, 2007). However, for a small change in output over a limited range from a near-steady state initial condition, coal power plants can respond very quickly. Although coal power plants build the foundation of base load generation given its share of grid capacity, they do have the ability to provide some load following.

Steam – Nuclear

Despite relatively low nuclear fuel costs, nuclear plant infrastructure development is capital intensive with payback periods of 25-40 years (Fettus, 2007). Economic and safety factors are the most significant consideration for the base operating point of nuclear power plants. Nuclear plants are normally operated at constant power with their turbine control valves being used to control steam pressure. Nuclear power plants are often used for base load and run at a high loading. Nuclear power plants in the U.S. had an average capacity factor of 91.1% in 2008, which was higher than any other generation type categorized by energy source (U.S. Energy Information Administration, 2009). Typically, nuclear plants power output can only be ramped slowly.

Steam – Gas

Steam power plants may also heat their boilers with gas combustibles. The operation of these plants is similar to other steam plants, predominantly providing base load generation. These types of plants are often cogeneration, where the waste heat is used for environmental heating purposes.

Internal Combustion Engine (I.C.E.) – Gas & Petroleum

Internal combustion engines can use a variety of fuels including natural gas, petroleum (including diesel), landfill gas, and others. The base operating point of internal combustion engine power plants is subject to the same utilization and emission and efficiency constraints of coal power plants. Internal combustion engines can be used for base load, load following, or peaking power generation.

Combined Cycle – Gas

Combined cycle gas turbine plants are driven by both steam and a gas, typically natural gas but sometimes also biogas or other gases. They generate power through a gas combustion turbine and use the waste heat to generate additional electricity from steam. These plants offer efficiencies of up to 60% (Siemens AG - Energy Sector, 2008). Combined cycle gas power plants often have control targets for steam pressure or exhaust temperature to maintain high system efficiency. The high system efficiency control modes are typically at conflict with providing frequency responsive capacity. Combined cycle – gas power plants offer little useful primary response and contribute to secondary response only with long time constants. Combined cycle – gas plants do however respond faster than steam power plants. For a large change in output ranges, the rate of change typically varies from 5% - 9% per minute (GE Energy, 2005), (Northwest Power Planning Council, 2002), (Vuorinen, 2007).

Gas Turbine

Gas turbines predominantly use natural gas for combustion, but may also use other combustible gases. The category of gas turbines includes both large industrial simple cycle gas turbines and also smaller aeroderivative gas turbines. The large industrial simple cycle gas turbines are specifically designed for power generation and offer better efficiency than the smaller aeroderivative gas turbines which are adapted from jet engines. Though, the size of aeroderivative turbines is favorable for peaking power generation. Gas turbines respond relatively slowly while traversing a large range of operation, at about twice the rate of combined cycle gas turbines (Vuorinen, 2007). Gas turbines do however respond quickly to small changes in output over a limited range from a near-steady state initial condition.

Gas turbines are less subject to the control decision of efficiency vs. load following generation found in combined cycle gas power plants. Gas turbines also have favorable emissions compared to coal power plants. These characteristics of gas turbines make them the preferred choice among thermal plants for operating as load following generation. Gas turbine power plants are however not exempt from economic and emission factors. One example of emission constraints for gas turbines are the combustion transition bands of large gas turbines with "dry low NOX" combustion systems. Load or temperature limits of gas turbines can also limit their load following capability (Pereira, 2006).

Hydropower

From here on, hydropower will be used to reference both conventional hydropower and pumped storage hydropower plants, the latter which provides bulk scale energy storage. Hydropower plants respond relatively consistently over a small or large range of operation. The power generation time constants for hydropower plants can range between 5 – 60 seconds, approximated as the combined effect of mechanical starting time, water starting time, and servo time constant (Runyan, Governor 101 - An Introduction to Hydroelectric Governing Theory, 2005), (Quiroga, 2000), (Arnautovic & Skataric, September 1991). Hydropower plant operation is not impacted by the emissions constraints of other forms of generation. However some hydropower plants such as run of the river or water management applications have a limited range of load following operation in order to satisfy flow and level requirements (Pereira, 2006). Also, some turbines experience rough zones which may or may not be avoidable. Although hydropower generation is subject to similar economic pressure to generate as much power as possible with the available resource, hydropower generation is widely accepted as an important component of both Primary Frequency Control and load following on the grid.

Wind

Wind deviates from traditional power generation due to variation in available power. Figure 3 shows the probability density function of wind speed for eight wind stations averaged over an area. Wind power is a "Must-Take" form of power generation where other sources of generation must smooth the variations in power supply from wind (Turchi, 2010). This variability in available wind power requires coordination of load following and peaking power generation.

At times, an operator may simply not select the wind generation for system or generation reasons. For example, the system may need a base load unit on line during off peak hours for system reasons and there is no opportunity for wind power to be dispatched. It takes time to bring thermal generation up to temperature when they are idle. Once up to temperature utilities want to dispatch their energy. According to (Fink, Mudd, Porter, & Morgenstern, 2009), wind power generation may sometimes be curtailed or saturated to a maximum generation output despite available wind capacity because: 1) "lack of available transmission during a particular time to incorporate some or all of the wind generation"; or 2) "high wind generation at times of minimum or low load, and excess generation cannot be exported to other balancing areas due to transmission constraints." One example of a curtailment operational procedure is where Bonneville Power Administration assigns generation limits to wind power plants when 90% of balancing reserves are deployed, and wind power plants must respond within 10 minutes otherwise Bonneville Power Administration may disconnect the plant (Fink, Mudd, Porter, & Morgenstern, 2009).

Unfortunately curtailment practices are in conflict with maximum capacity utilization for favorable return on investment, which is undesirable given that the majority of wind infrastructure is relatively new on the U.S. grid. Curtailment may be avoided by pairing wind generation with energy storage. Currently pumped storage hydropower plants are the only substantial bulk scale energy storage available on the grid.

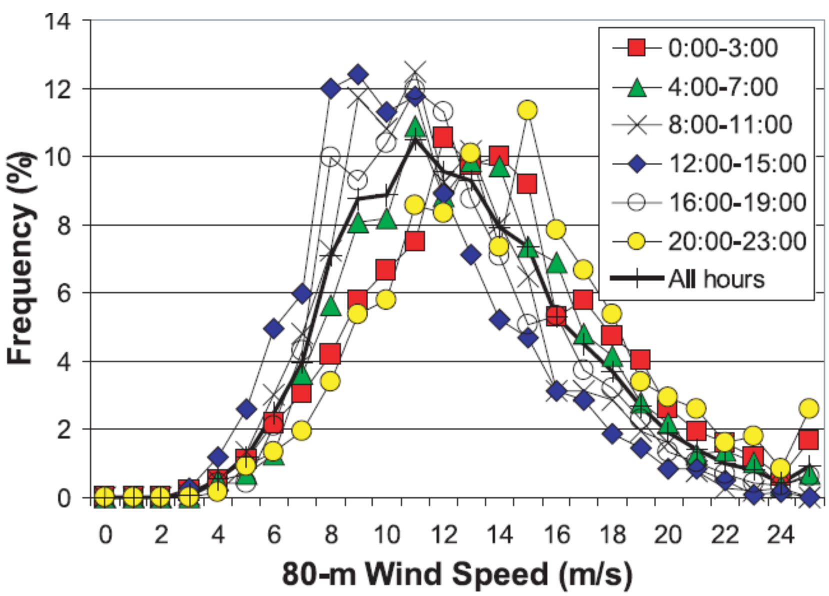

Figure 3: Eight-Station Area-Averaged Wind Speed. Source: (Archer & Jacobson, 2003)

Solar – Photovoltaic (P.V.) & Thermal

There are two types of solar power plants: photovoltaic and thermal. Solar photovoltaic (P.V.) plants use the photoelectric effect to transform light energy directly into electrical energy, using a variety of solar cell technologies and sometimes using concentrated light. Solar thermal plants use the sun as the heat source, and concentrate sunlight using mirrors to heat a transfer fluid which is then used to produce hot water or steam. Solar power exhibits variability in power generation just as wind power. Solar is also a "Must-Take" form of power generation, when not coupled with storage technologies (Turchi, 2010). Figure 4 shows the temporal variation of irradiance across the United States.

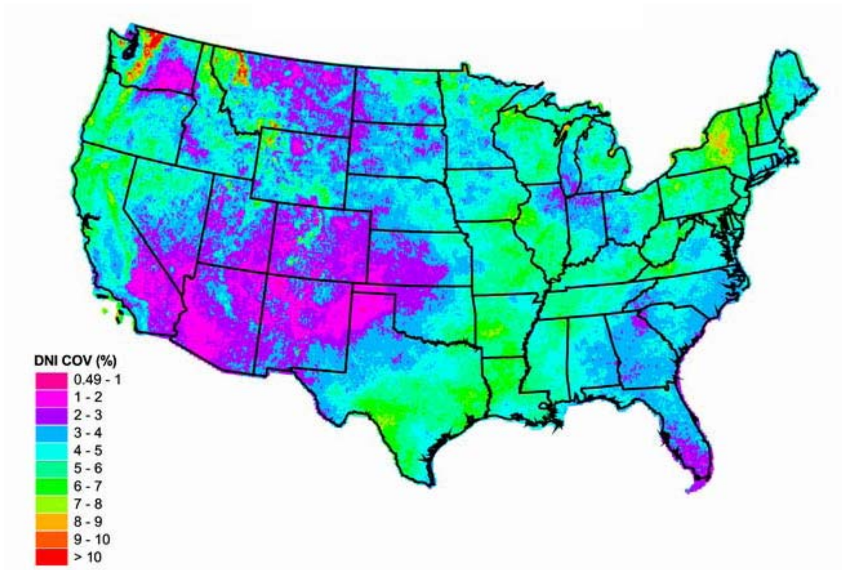

Figure 4: Interannual Direct Normal Irradiance Coefficient of Variation (%), 1998-2005. Source: (Wilcox & Gueymard, 2010)

Simple Primary Frequency Control Model for a Collection of Power Generating Turbines

Nomenclature

$$\begin{aligned}
\sigma &= \text{governor droop (constant 5\%)} \\
f_{Grid}^{set} &= \text{nominal grid frequency setpoint (constant 60 Hz)} \\
P_{Dist} &= \text{Power disturbance on grid, from generation dropout (negative MW)} \\
\Delta P_T &= \text{collective deviation in grid power generation from pre - event value (MW)} \\
\Delta f_{Grid} &= \text{change in grid frequency (Hz)} \\
C_f &= \text{turbine capacity (MW)}
\end{aligned} \tag{2}$$

All forms of generation have different dynamic characteristics depending on the magnitude of the load change and the initial steady state operating point due to system nonlinearities. However, for small load changes on the grid which are typical of a disturbance where Primary Frequency Control response takes place, a nonlinear dynamic model can be linearized about the initial conditions prior to the disturbance. Figure 5 is generalizes a turbine model with capacity C_f, droop feedback, and a governor and turbine modeled as $H(s)$.

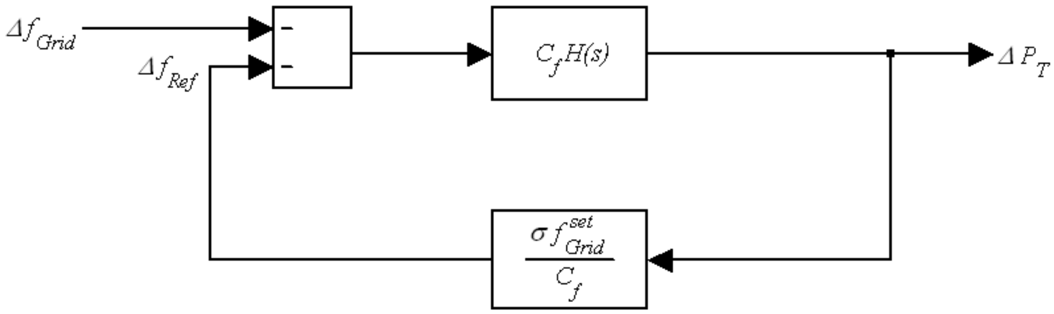

Figure 5: General linearized turbine model

The transfer function for Figure 5 is:

$$\frac{\Delta P_T}{\Delta f_{Grid}} \approx -\frac{C_f H(s)}{1+\sigma f_{Grid}^{set} H(s)} \qquad \textbf{(3)}$$

Since governing provides for steady state tracking due to an integral component, $H(s)$ has a high gain at low frequencies. This transfer function can therefore be approximated using $L(s)$ which has a unity gain at steady state:

$$\frac{\Delta P_T}{\Delta f_{Grid}} \approx -\frac{C_f}{\sigma f_{Grid}^{set}} L(s) \qquad \textbf{(4)}$$

(Undrill, 2010) proposes such a linearized model for a group of power plants of a given type with two dominant poles and a single dominant zero, that is suitable for a change of less than 3% power generating turbine capacity, or 0.09 Hz.

$$L(s) = \frac{T_z s + 1}{(T_a s + 1)(T_b s + 1)} \qquad \textbf{(5)}$$

Where

$$\begin{aligned} C_{fn} &= \text{Available unit capacity for load following for the nth generator} \\ T_{zn} &= \text{Zero time constant for the nth generator} \\ T_{an}, T_{bn} &= \text{Pole time constants for the nth generator} \end{aligned} \qquad \textbf{(6)}$$

The model of Equation (4) is shown in Figure 6.

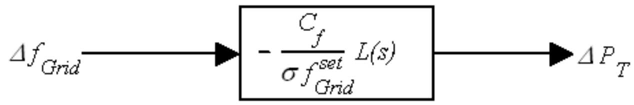

Figure 6: Simplified model for small frequency (±0.09 Hz) and load changes (±3% capacity).

Figure 7 approximates a system that is a collection of power generating turbines following the model of Figure 6.

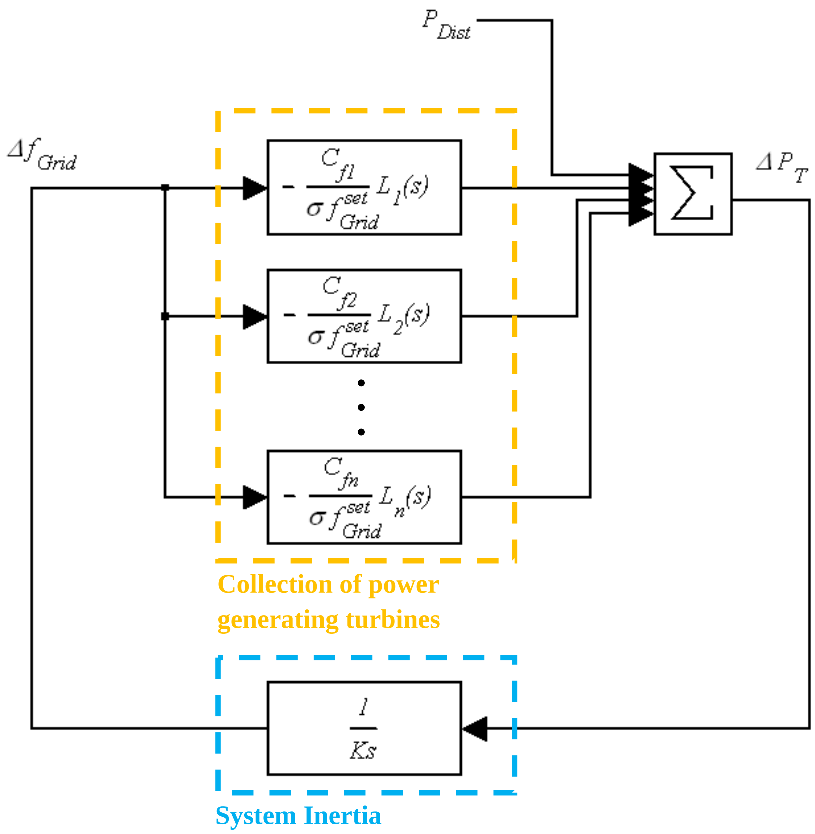

Figure 7: Linearized model for a collection of power generating turbines subject to small frequency and load changes.

Simulation of Primary Frequency Control on the Western Electricity Coordinating Council's Grid

Table 2 estimates the maximum available capacity for each generation type in the Western Electricity Coordinating Council's (WECC) grid for 2008, according to data from the U.S. Energy Information Administration and the Canadian Energy Association. The model of Figure 7 requires knowledge of the online frequency responsive capacity of each generation type, which is also summarized in Table 2 for WECC in 2008 and estimated as follows:

Total Online Frequency Responsive Capacity on WECC

(Martinez, Xue, & Martinez, 2010) reports a frequency response metric for WECC of 1,223 MW/deci-Hz (equivalently 12,230 MW/Hz) in 2008. This frequency response metric as defined in (Martinez, Xue, & Martinez, 2010) "relates the change in the balance between load and generation, called MW imbalance to the associated change to settling frequency." This frequency response metric is derived from loss of generation events and has been adjusted for frequency bias, Area Control Error (ACE), and post-event frequency transient and noise (Martinez, Xue, & Martinez, 2010). The reciprocal of this value is the steady state transfer function of $\Delta f_{Grid} / P_{Dist}$ from Figure 7, which can also be derived from the steady state droop equation.

$$\left.\frac{\Delta f_{Grid}(s)}{P_{Dist}(s)}\right|_{s=0} = \frac{\sigma\, f_{Grid}^{set}}{\sum_{i=1}^{n} C_{fi}} \qquad (7)$$

After substitution,

$$\sum_{i=1}^{n} C_{fi} = \sigma\, f_{Grid}^{set} \cdot 12{,}230 = 36{,}690 \text{ MW} \qquad (8)$$

Equation (8) estimates that the average total online frequency responsive capacity on WECC was about 36,690 MW in 2008.

Online Frequency Responsive Capacity – Not Typically Load Following Generation

As earlier outlined in Table 1, some generation types are used almost exclusively for base load including: Steam – Coal & Other, Combined Cycle – Gas, Steam – Nuclear, Steam – Gas, and Internal Combustion Engine (I.C.E) – Gas & Petroleum. Approximately 1% of total generating capacity of these plants is assumed to be frequency responsive capacity, as shown in Table 2.

Online Frequency Responsive Capacity - Typically Load Following Generation

Load following generation is predominantly derived from hydropower or gas turbines, as outlined in Table 2. Due to a lack of available data regarding how much these generation types are contributing individually, a sensitivity analysis is undertaken. If a small percentage (1%) of each generation type is assumed as load following capacity credited to base-loaded generation, that leaves a remaining combined responsive capacity for hydropower and gas turbines of 35,542 MW. The fraction of gas turbine capacity providing online frequency responsive capacity is defined as the sensitivity parameter, X. Therefore, the online frequency responsive capacity for gas turbines is taken as 17,746•X (MW) and the online frequency responsive capacity for hydropower is taken as 35,542 - 17,746•X (MW). These capacities are indicated in Table 2.

Model Dynamic Parameters

In order to apply the model of Figure 7, the time constants of Table 3 are used. The small signal time constants for steam – coal, steam – nuclear, and steam - gas power plants are taken from the steam turbine parameters from (Undrill, 2010). The small signal time constants for hydropower plants are taken from the hydro turbine parameters from (Undrill, 2010). Due to the faster response for load changes on combined cycle – gas, gas turbine, and internal combustion engine – gas & petroleum plants, the dominant pole and zero time constants are taken to be 2/3 the value for steam turbines.

Power Generation Type	Total Generating Capacity (MW)[4]	C_f, Estimated Online Frequency Responsive Capacity (MW)
Steam – Coal & Other[5]	43,150	432
Hydropower	61,277	35,542 - 17,746•X
Combined Cycle – Gas	41,489	415
Steam – Nuclear	9,463	95
Steam – Gas	19,496	195
Gas Turbine	17,746	17,746•X
Wind[6]	7,434	
Internal Combustion Engine (I.C.E) – Gas & Petroleum	1,172	12
Solar – Photovoltaic (P.V.) & Thermal[6]	526	
Total	201,753	36,690

Table 2: Maximum Online Capacity and Online Frequency Responsive Capacity of Different Generation Types on the WECC Grid in 2008

Power Generation Type	T_a (seconds)	T_b (seconds)	T_z (seconds)
Steam – Coal & Other[5]	0.5	10.0	3.0
Hydropower	2.5	40.0	4.0
Combined Cycle – Gas	0.5	6.6	2.0
Steam – Nuclear	0.5	10.0	3.0
Steam – Gas	0.5	10.0	3.0
Gas Turbine	0.5	6.6	2.0
Wind[6]			
Internal Combustion Engine (I.C.E) – Gas & Petroleum	0.5	6.6	2.0
Solar – Photovoltaic (P.V.) & Thermal[6]			

Table 3: Model Parameters for Primary Frequency Response Simulation

For simulation, a power generation dropout of 500 MW is used. The system inertia constant is taken as K = 8,806 MJ/Hz. The model of Figure 7 with parameters from Table 2 and Table 3 is simulated for both X = 33% and X=66%.

Figure 8 shows the grid power and frequency response during the critical period of 30 seconds following the event before Automatic Generation Control begins to intervene. The Primary Frequency Control

[4] Estimated from summer capacities reported in (U.S. Energy Information Administration, 2008) for US states predominantly in WECC (Washington, Oregon, California, Idaho, Nevada, Montana, Utah, Arizona, Wyoming, Colorado, and New Mexico) and average generation reported in (Canadian Electricity Association, 2009) for Canadian provinces predominantly in WECC (British Columbia and Alberta).

[5] The coal category groups other steam plants with small representation including: geothermal, biomass, and petroleum.

[6] These are "Must-Take" forms of generation and do not contribute to Primary Frequency Control.

reverses the drop in grid frequency (frequency nadir) at around 6 seconds, which is comparable with real data found in (Eto, et al., 2010) for WECC. Figure 9 and Figure 11 shows the power contribution by generation type for the 30 seconds following the event, for *X*=33% and *X*=66%, respectively. Figure 10 and Figure 12 show how the power contribution compares between hydropower and gas turbines for *X*=33% and *X*=66%, respectively. The importance of the quick response of gas turbines in the first 10 seconds after a frequency event can be seen in Figure 10 and Figure 12. Figure 13 shows how the Primary Frequency Control response from hydropower varies with *X*, or the percent of gas turbine capacity that is online and available as frequency responsive capacity, at 10 seconds following a frequency event.

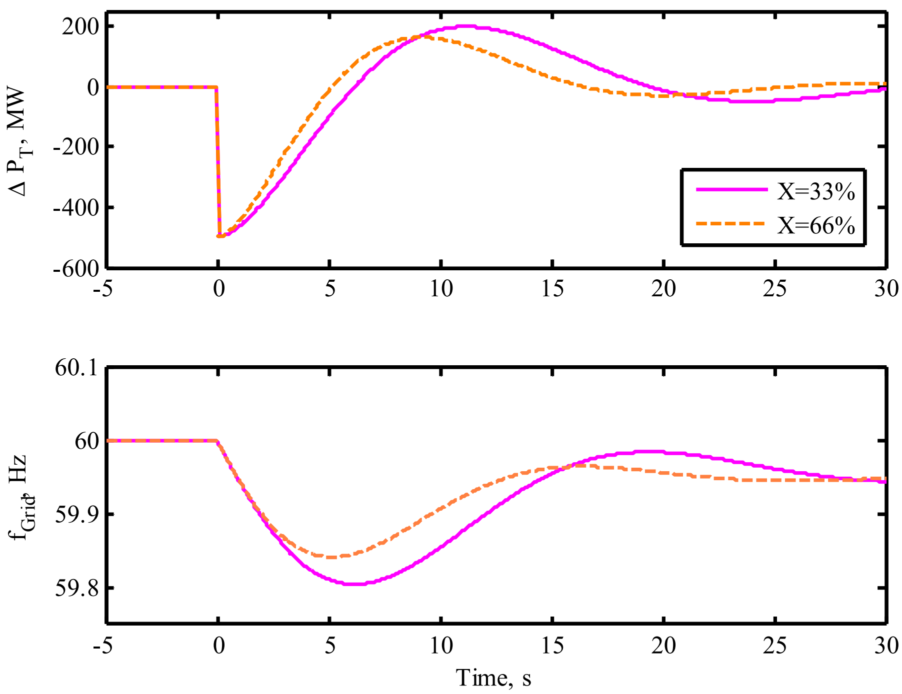

Figure 8: Simulated Turbine Power and Frequency Response after a Power Generation Dropout of 500 MW on WECC, *X*=33% and *X*=66%

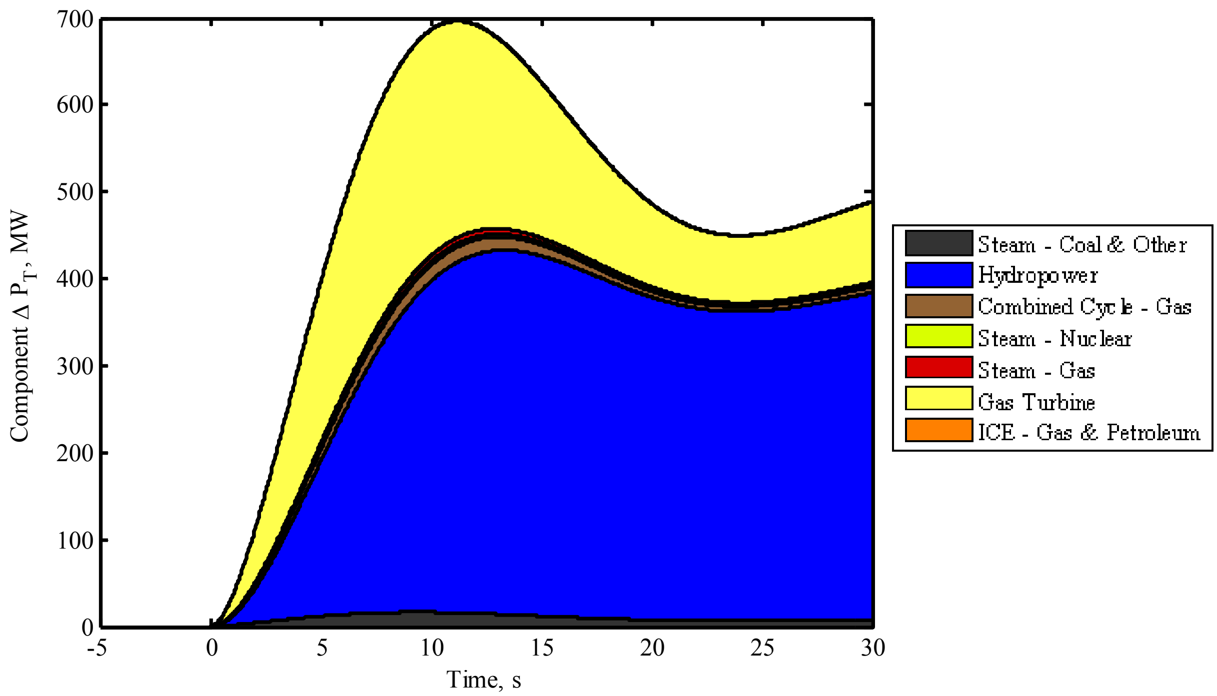

Figure 9: Simulated Power Contribution by Generation Type after a Power Generation Dropout of 500 MW on WECC, *X* = 33%

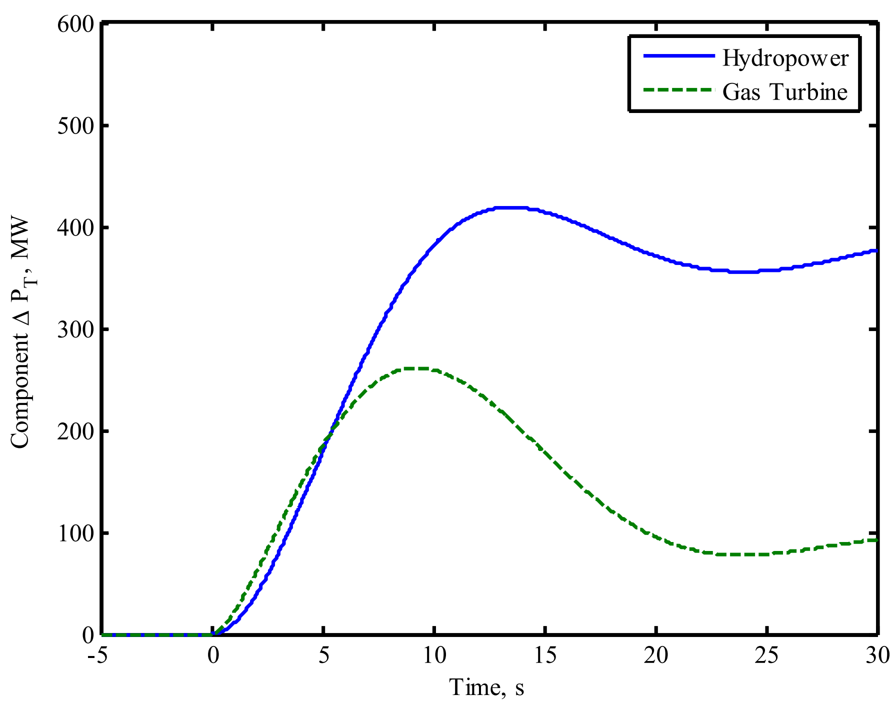

Figure 10: Power Contribution from Hydropower and Gas Turbines after a Power Generation Dropout of 500 MW on WECC, *X*=33%

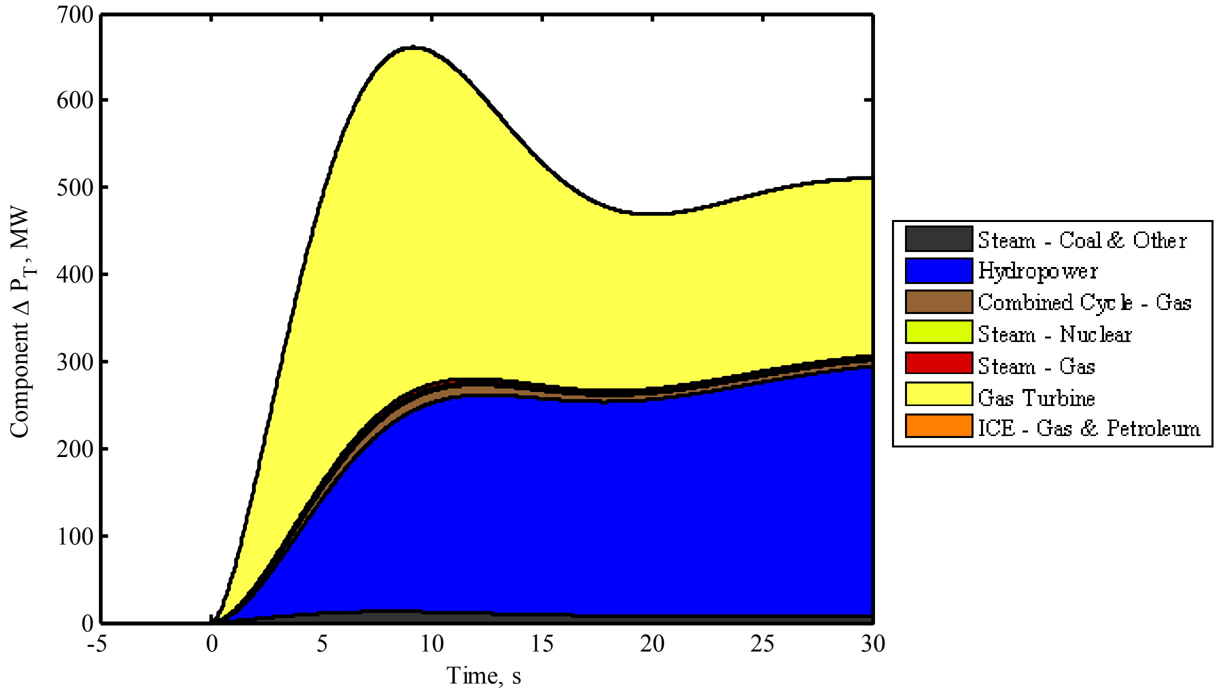

Figure 11: Simulated Power Contribution by Generation Type after a Power Generation Dropout of 500 MW on WECC, *X* = 66%

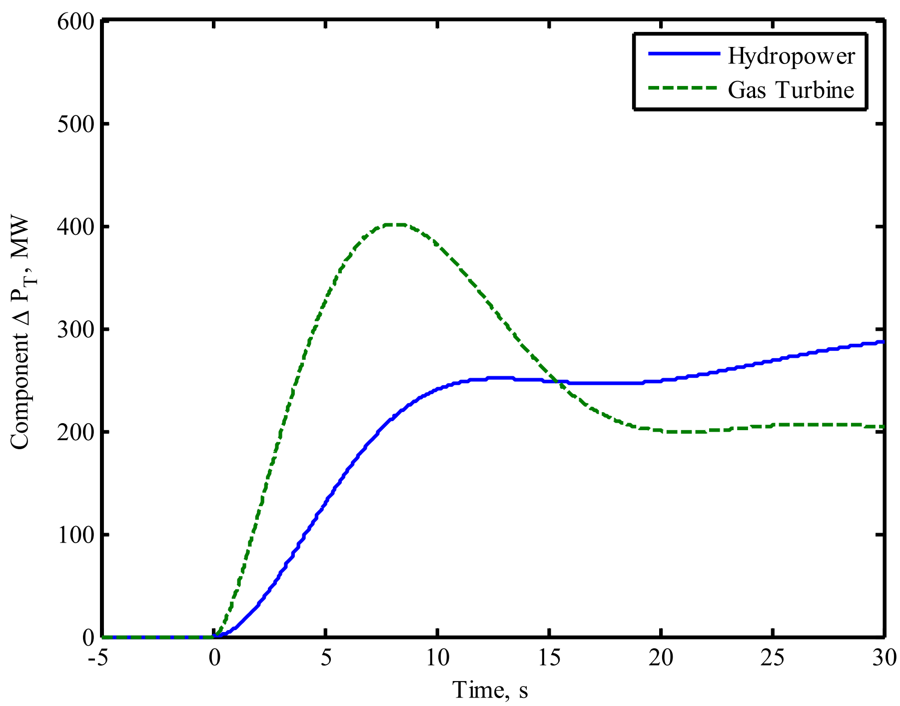

Figure 12: Power Contribution from Hydropower and Gas Turbines after a Power Generation Dropout of 500 MW on WECC, *X* = 66%

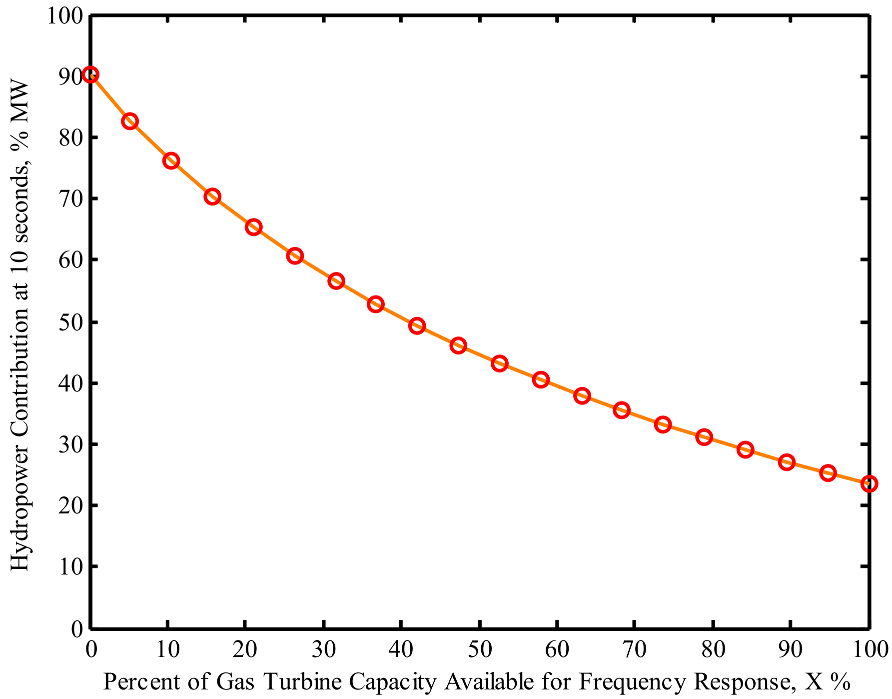

Figure 13: Percent of Primary Frequency Control Response from Hydropower at 10 seconds after a Power Generation Dropout of 500 MW, Sweep of *X* Values

Conclusion

Hydropower and gas turbine power plants contribute a large proportion of Primary Frequency Response. Steam plants powered by coal, gas, and nuclear fuels and combined cycle gas plants contribute a small percentage of Primary Frequency Response. Wind and solar power make no measurable contribution to Primary Frequency Response. Figure 13 estimates that for the WECC grid as a whole in 2008, hydropower generation contributed between 25-90% of the Primary Frequency Control response in the first 10 seconds after an under-frequency event, before intervention from Automatic Generation Control. If it is assumed that about 33% of gas turbine capacity was available online and as frequency responsive capacity (*X*=33%), then hydroelectric generation contributed approximately 55% of the Primary Frequency Response at 10 seconds after a power dropout event.

This preliminary study provides motivation for the following:

1. Perform a more detailed study that:
   a. Models plant controllers and plants in more detail, representative of measured data and
   b. Includes historic data on frequency responsive capacity for each generation type.
2. Hydroelectric power could provide an even larger component of grid frequency stability. There may be ineffective capacity because of one of several possible reasons:
   a. Run of river limitations cause water availability to exceed the rated generation capacity where output is saturated, and governing is not possible.
   b. Some hydropower plants are used for water management, which may sometimes have conflicting control objectives with load following (Pereira, 2006).

c. Some hydro plants may be excluded from NERC frequency response requirements (Fluegge).
d. The operating philosophy of utility companies may be not to use all possible hydropower capacity for Primary Frequency Control.
e. Governors for some hydropower plants may not be regularly maintained or replaced. (Runyan & Mato, Monitoring the Health of Mechanical Governors, 2007) and (Kroner & Bérubé, 2008) show that proper maintenance and tuning of mechanical governors does improve Primary Frequency Control for hydropower plants. Under certain conditions, governor replacement may also be warranted. A sample decision process for governor replacement is available in (Clarke-Johnson & Ginesin, 2007). For every percent of hydro generation added as frequency responsive capacity, there is about 0.5% improvement in grid Primary Frequency Control (*X*=33%) for WECC.

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