Primary frequency control reserves are adequate, if, following a sudden largest loss of generation[1], the primary frequency control actions provided by these reserves successfully arrest and stabilize frequency decline prior to the dropping of firm customer loads through under-frequency load shedding. The most important aspect of frequency behavior following the sudden loss of generation is the point at which frequency is arrested or the frequency nadir. If frequency nadir is greater than (i.e., frequency is arrested above) the highest set point for under-frequency load shedding, then the primary frequency control reserves that were in place at the time generation was lost were adequate. If, however, frequency decline is not arrested and frequency crosses below the highest set point, firm customer loads will be dropped through the actions of under-frequency load shedding. This means the primary frequency control reserves that were in place were inadequate [LBNL report, 2010].

Frequency response is the traditional metric used to describe how an interconnection has performed in stabilizing frequency after the loss of generation. Frequency response is measured by relating the size of the generation lost to the resulting net change in system frequency once frequency has been stabilized (at Point B), see textbox below for NERC ALR1-12 metric.

One reason the traditional definition of frequency response is based on settling frequency (Point B) is that until recently power system monitoring technologies could not reliably measure frequency nadir (Point C). Frequency nadir could only be studied with simulation tools. Advances in power system monitoring technologies have now made it possible to measure frequency nadir in the field [LBNL report, 2010].

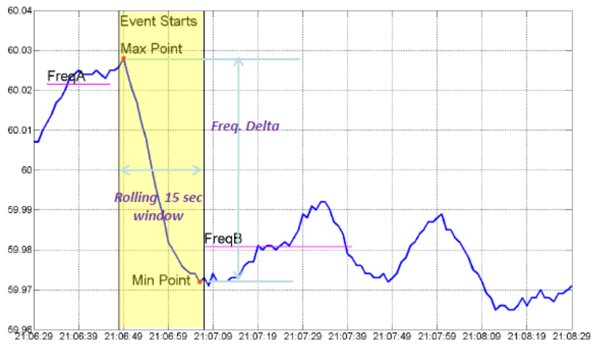
ALR1-12: This metric is used to track and monitor Interconnection's frequency response. It is defined as a sum of the change in demand plus the change in generation, divided by the change in frequency expressed in MW/0.1 Hz. The metric measures the average Frequency Response where frequency drops more than Interconnection's defined threshold (Table 9 below). High resolution frequency measurements (F-net and…) are used to produce frequency time series with 1-second resolution, which is used in ALR1-12 analysis.

While the calculations may show trends from year to year no attempts has been made in this analysis to determine or state what indicates the "acceptable" level of frequency response. Rather they show the relative performance from year to year and can be basis for future root-cause analysis. (http://www.nerc.com/pa/RAPA/ri/Pages/InterconnectionFrequencyResponse.aspx)

Figure below shows the criteria for calculating average values A and B. The event starts at time t ±0. Value A is the average from t -16 to t -2 and Value B is the average from t +20 to t +52. The difference of value A and B is the change in frequency used for calculating Frequency Response. These lengths of time used to calculate these values accounts for the variability in System Control and Data Acquisition (SCADA) scan rates that vary from two to six seconds in the multiple-Balancing Authority interconnections.

Commented [MJ1]: Bob mentioned another high resolution data source that's used here?

[1] Largest generation loss is defined as largest category C(N-2) event, except for Eastern Interconnection, which uses largest event in the last 10 years[NERC BAL-003-1]

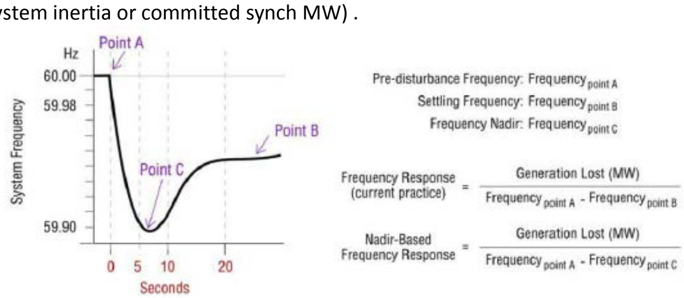


Value A (average t -16 to t - 2) & **Value B** (average t +20 to t + 52)

Table 9: Frequency Event Triggers			
Interconnection	ΔFrequency (mHz)	MW Loss Threshold	Rolling Windows (seconds)
Eastern	36	800	15
Western	70	700	15
ERCOT	90	450	15
Québec	140	450	15

We propose Measure 4 to enhance the traditional frequency response metric and focus on **all** aspects of frequency response that are important for reliability immediately following a loss-of-generation event which are:

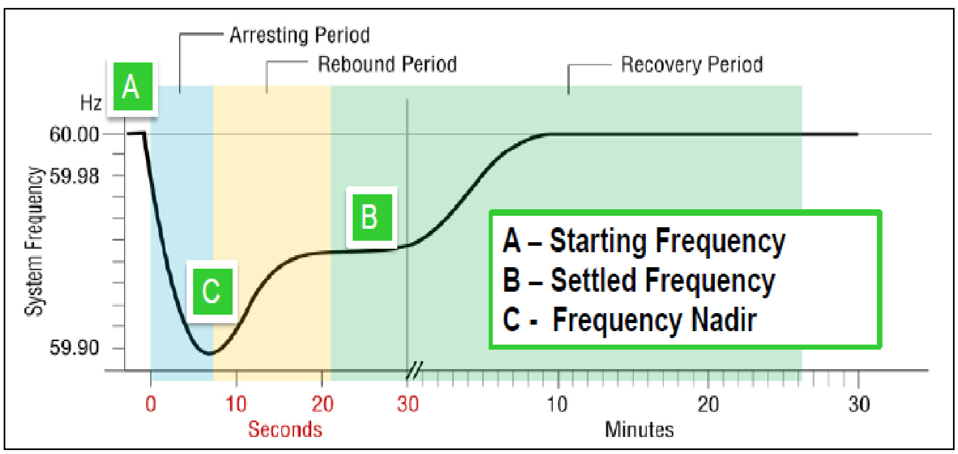
1. **<u>A to C measure</u>** is calculated **nadir-based frequency response** in MW/0.1 Hz (unit loss divided by A to C frequency deviation) trended year to year versus system conditions (e.g. net load or system inertia or committed synch MW) .



This measure captures the impacts of inertial response, load response (load damping) and partially governor response (governor response is deployed immediately after frequency falls outside of a pre-set dead band, however, depending on generator technology, full governor response is deployed in about 12-16 seconds). Trending this measure year to year will capture effect of changes in generation mix and load characteristics and help to identify needs for fast power injection from e.g. battery storage, or load resources with under-frequency relays to provide fast frequency control and assist in arresting system frequency after large generation loss.

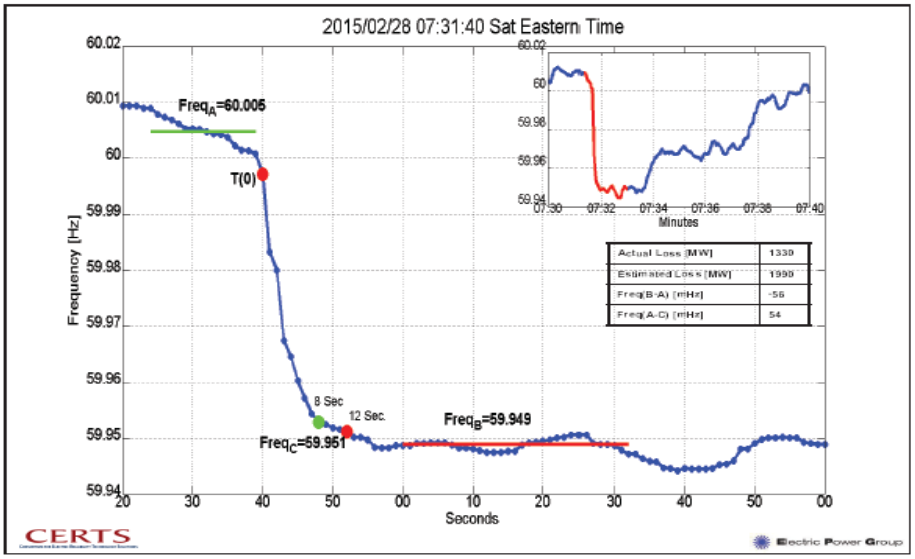
Commented [MJ2]: I know this is the time frame for ERCOT but not sure about other interconnects

2. **A to B measure** captures the speed and effectiveness of primary frequency response. Here ALR1-12 in MW/0.1 Hz could be trended year to year versus system conditions. ALR1-12 metric is already being used. However trending it vs time does not provide information on how at similar system conditions the response is changing year to year. So this would be an improvement that the group could recommend.
3. **B to C measure** this could be ratio on its own or in form of ratio between 1 and 2 above. This measure should also be trended year to year versus system conditions since B to C would be related to system inertia and speed of governor response of committed generators.
4. **C to C' measure** in Hz trended year to year versus system conditions. In Eastern Interconnect difference between Point C and Point C' (59-78 seconds after an event due to governor response withdrawal[2]). While ALR1-12 data does not contain C', original frequency data with 1-second resolution (captures 300 seconds of an event) can be used. In Eastern Interconnect, trending the difference between Point C and Point C' for similar size events will capture if generators are working with vendors to adjust plants DCS controllers and avoid governor response withdrawals[3].



[2] Point C' is observed in Eastern Interconnect after large generator trip. Few seconds after initial governor response from generating units, their active power set point control takes over bringing generation units back to their original operating point, which results in withdrawal of governor response and further frequency decrease as a result. Point C' may be lower than initial frequency nadir (Point C).

[3] The proposed control algorithm to avoid governor response withdrawal was presented during NERC Frequency Response Initiative webinar on April 7, 2015.



It should be pointed out that currently, there is no problem with frequency nadir in any of the 4 interconnections. We recommend this measure for the interconnects to be able to see the changes year to year and if there is a concern more detailed analysis will be needed to understand the reason behind declining trends.

ERCOT Example.

Below are two plots for ERCOT based on 2010-2014 event data. First plot shows frequency nadir for the whole year of events (the largest events were excluded since these being single event majorly affect the trend lines). From this figure the 2010-2011 nadirs are lower for the same event size the nadir is improving since, even though there is more wind generation installed each year (see Figure 3 below) and system inertia is getting lower during high wind low load conditions. The reason behind frequency nadir improvement are as follows:

- During transition from zonal to nodal extensive governor testing was done at all plants
- Since March 2012 wind generators are required to provide governor like response. This response is faster than governor response from conventional generators. Governor-like response from wind generators is available at overfrequency any time a generator is in operation and at underfrequency when a wind generator is curtailed. Until completion of CREZ transmission project (at the end of 2013) wind generation in West Texas was oftentimes curtailed and therefore capable of governor line response at underfrequency events.

- In January 2014 BAL-001-TRE standard was approved 1/16/2014 with effective date 4/1/2014 and implementation plan for 30 month, however during the development of the standard many generators tested their governors with more narrow governor deadband settings as prescribed by the standard and then did not change the settings back.

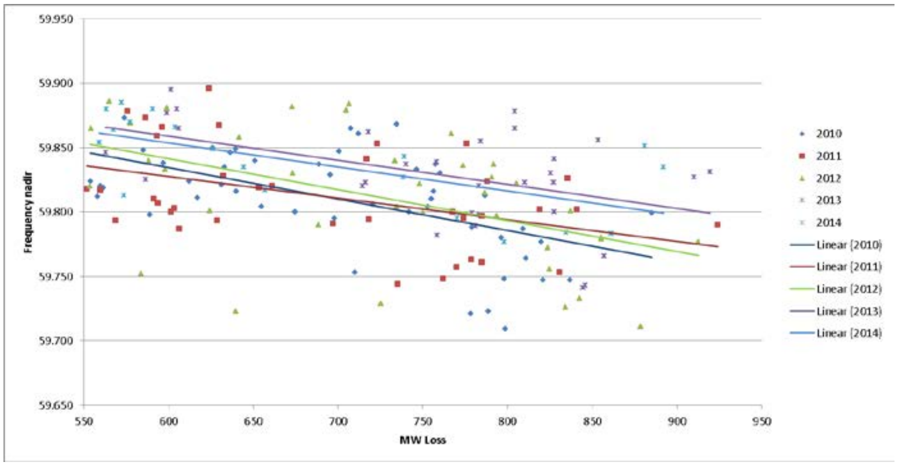


Figure 1: Frequency nadir (point C) in ERCOT 2010-2014.

The second plot shows **nadir-based frequency response** as a function of system net load (load minus wind).

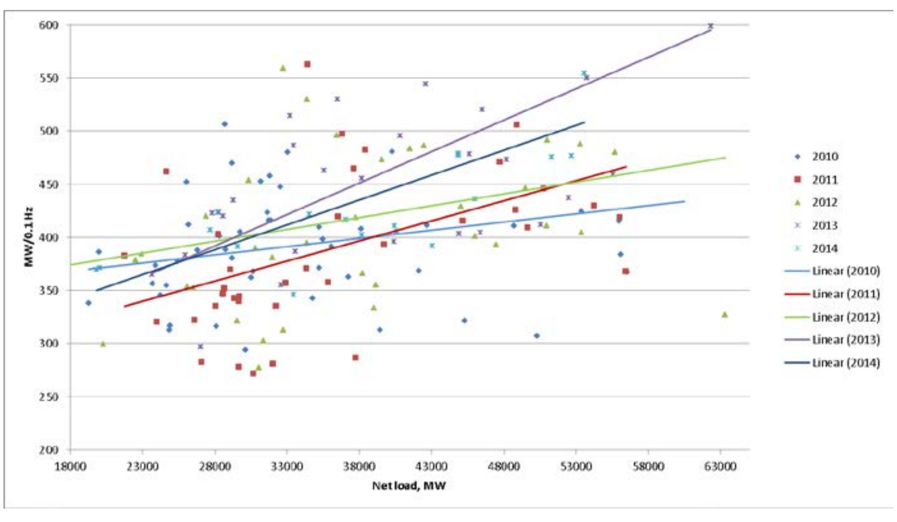


Figure 2: Frequency nadir expressed as MW/0.1 Hz in ERCOT 2010-2014.

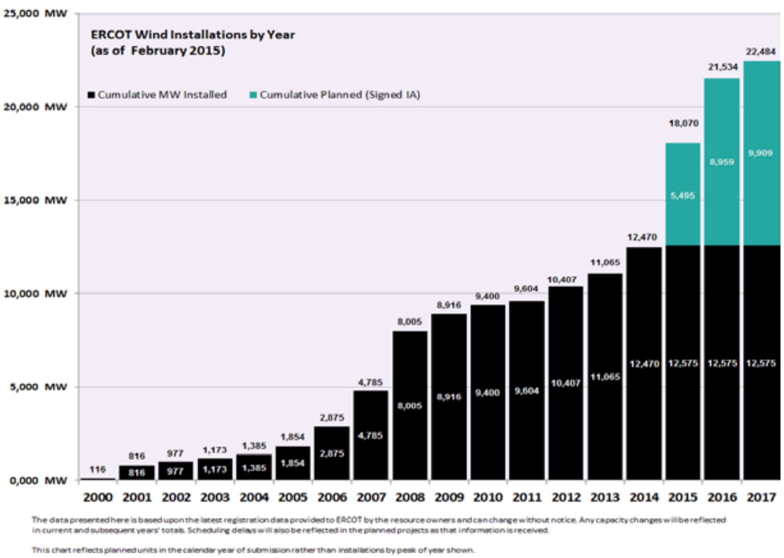


Figure 3: ERCOT Wind Generation Installations by year (as of February 2015)