

**2008-2009 ERCOT LOADS ACTING AS A RESOURCE  
CAPABILITY STUDY**

**APRIL 2009**

**PREPARED FOR THE ERCOT RELIABILITY AND OPERATIONS SUBCOMMITTEE  
BY THE ERCOT DYNAMICS WORKING GROUP**

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**STUDY GROUP**

## 2008 Dynamics Working Group

<b>DWG MEMBER</b>	<b>COMPANY</b>
Anthony Hudson, Chair	Texas-New Mexico Power Company
Jose Conto	ERCOT System Planning
John Schmall	ERCOT System Planning
David Milner, Vice Chair	City Public Service
Vance Beauregard	American Electric Power
Roy Boyer	Oncor
Reza Ebrahimian	Austin Energy
Shun-Hsien Huang	ERCOT Operations Support
David Mercado	Centerpoint Energy
Tom Bao	Lower Colorado River Authority
John Moore	South Texas Electric Cooperative

**DISCLAIMER**

The Electric Reliability Council of Texas (ERCOT) Dynamics Working Group prepared this document. Conclusions reached in this report are a “snapshot in time” that can change with the addition, or elimination, of plans for new generation, transmission facilities, equipment, or loads.

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As the independent system operator for the region, ERCOT schedules power on an electric grid that connects 38,000 miles of transmission lines and more than 550 generation units.

ERCOT also manages financial settlement for the competitive wholesale bulk-power market and administers customer switching for 6 million Texans in competitive choice areas.

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ERCOT's members include consumers, cooperatives, independent generators, independent power marketers, retail electric providers, investor-owned electric utilities (transmission and distribution providers), and municipal-owned electric utilities.

## **EXECUTIVE SUMMARY**

### ***INTRODUCTION***

In October 2007, the ERCOT Technical Advisory Committee (TAC) approved a proposal to change the Responsive Reserve Service (RRS) obligation from the existing 2300 MW to 2800 MW. A current ERCOT operating guide rule allows for 50% of the ERCOT RRS obligation to be composed of Loads Acting as a Resource (LaaR) tripped at 59.7 Hz, with the remainder being spinning reserves. The current rule, however, is based upon the previous RRS obligation of 2300 MW. This translates to a maximum allowable 1150 MW of LaaRs tripped at 59.7 Hz. At this maximum level of LaaRs, there remains a substantial spinning reserve pool of 1650 MW under the new 2800 MW RRS obligation.

ROS assigned this study to the Dynamics Working Group (DWG) to answer questions originally raised by the ERCOT Long Term Solutions Task Force (LTSTF). The LTSTF asked whether reliability concerns would be raised by increasing LaaRs, tripped at 59.7 Hz, based upon the new RRS obligation of 2800MW. Furthermore, the LTSTF asked how much higher a LaaR maximum limit is possible if frequency tiered deployment were considered.

### ***STUDY OBJECTIVE***

There are three objectives of this study.

1. Determine the LaaRs percentage of 2800 MW RRS obligation, tripped at 59.7 Hz, where reliability concerns are raised.
2. Determine the incremental LaaRs percentage of 2800 MW RRS obligation, tripped at 59.8 Hz, where reliability concerns are raised.
3. Pursuant to the ROS January 2009 request, determine the LaaRs percentage of 2300 MW RRS obligation, tripped at 59.7 Hz, where reliability concerns are raised.

### ***STUDY RESULTS***

Because system inertia is at the lowest levels during light loading, conditions are most favorable for system frequency overshoot. Consequently, the critical operating scenarios for reliable deployment of LaaRs are during periods of light loading. The most significant variables to consider in determining the maximum amount of LaaRs that can be deployed via underfrequency relaying are the frequency trip settings of the LaaR relays. The worst case scenarios for frequency overshoot occur when all of the LaaRs trip at the same frequency set- point. Intermediately, frequency overshoot can be depressed to varying degrees when the frequency set-points of the LaaR relays are spread out over a range of frequencies. Other variables having a more limited relationship with the maximum amount of LaaRs deployable by underfrequency relaying are the geographical locations of the LaaRs. Tables 1 and 2 summarize the various limits on the amount of LaaRs deployable at the 59.7 Hz tier and the conditions associated with each limit.

**Table 1 – Summary of LaaRs Limits at the 59.7 Hz Tier, 2800 MW RRS**

LOCATION OF LaaRs	RELAY TRIP SETTING (Hz) <sup>†</sup>	LaaRs LIMIT (% of 2800 MW)	LIMIT BASIS
Existing locations	Existing trip settings: 9.1% @59.8 Hz 0.9% @59.72 Hz 1.4% between 59.71 and 59.72 Hz 10.7% @59.71 Hz 25.4% between 59.70 and 59.71 Hz 52.5% @59.70 Hz	65	Overshoot greater than or equal to 60.4 Hz.
Existing locations	Modified version of the existing trip settings: 0.9% @59.72 Hz 1.4% between 59.71 and 59.72 Hz 10.7% @59.71 Hz 25.4% between 59.70 and 59.71 Hz 61.6% @59.70 Hz	60	
Existing locations	59.72	55	
Uniformly distributed throughout ERCOT	59.74+	55	
Lumped in NTX CSC zone	59.72	55	
Lumped in STX CSC zone	59.74	50	
Lumped in WTX CSC zone	59.72	50	
Lumped in HOU CSC zone	59.74+	50	

<sup>†</sup>The relay trip setting data in row 1 of this table is representative of the existing LaaRs in ERCOT. The relay trip setting numbers in rows 3 through 8 are maximum LaaR trip frequencies assuming all of the LaaRs specified in the “LaaRs LIMIT” column are tripped at the same frequency.

**Table 2 – Summary of LaaRs Limits at the 59.7 Hz Tier, 2300 MW RRS**

LOCATION OF LaaRs	RELAY TRIP SETTING (Hz) <sup>†</sup>	LaaRs LIMIT (% of 2300 MW)	LIMIT BASIS
Existing locations	Existing trip settings: 9.1% @59.8 Hz 0.9% @59.72 Hz 1.4% between 59.71 and 59.72 Hz 10.7% @59.71 Hz 25.4% between 59.70 and 59.71 Hz 52.5% @59.70 Hz	70	Overshoot greater than or equal to 60.4 Hz.
Existing locations	Modified version of the existing trip settings: 0.9% @59.72 Hz 1.4% between 59.71 and 59.72 Hz 10.7% @59.71 Hz 25.4% between 59.70 and 59.71 Hz 61.6% @59.70 Hz	65	
Existing locations	59.74	60	
Uniformly distributed throughout ERCOT	59.72	60	
Lumped in NTX CSC zone	59.78+	55	
Lumped in STX CSC zone	59.74	55	
Lumped in WTX CSC zone	59.78+	50	
Lumped in HOU CSC zone	59.78+	55	

<sup>†</sup>The relay trip setting data in row 1 of this table is representative of the existing LaaRs in ERCOT. The relay trip setting numbers in rows 3 through 8 are maximum LaaR trip frequencies assuming all of the LaaRs specified in the “LaaRs LIMIT” column are tripped at the same frequency.

Results from simulations of LaaRs deployed at the 59.8 Hz tier indicate such LaaRs cannot be reliably deployed with the 59.7 Hz tier LaaRs operated at the critical levels identified in tables 1 and 2. The maximum amount of LaaRs and corresponding maximum relay trip settings that can be reliably deployed at the 59.8 Hz tier is a function of where limits are established for the amount of LaaRs and corresponding relay trip settings at the 59.7 Hz tier. Therefore, the DWG will need guidance from ROS on where the 59.7 Hz tier limits will be set in order to define LaaR limits for the 59.8 Hz tier.

Section 6.10.3.2 of the ERCOT Protocols allow a LaaR to be deployed at up to 150% of the amount requested by ERCOT at the time of testing the LaaR. This potential variance between contracted and actual LaaR amount should be considered when establishing LaaR limits.

## **INTRODUCTION**

In October 2007, the ERCOT Technical Advisory Committee (TAC) approved a proposal to change the Responsive Reserve Service (RRS) obligation from the existing 2300 MW to 2800 MW. A current ERCOT operating guide rule allows for 50% of the ERCOT RRS obligation to be composed of Loads Acting as a Resource (LaaR) tripped at 59.7 Hz, with the remainder being spinning reserves. The current rule, however, is based upon the previous RRS obligation of 2300 MW. This translates to a maximum allowable 1150 MW of LaaRs tripped at 59.7 Hz. At this maximum level of LaaRs, there remains a substantial spinning reserve pool of 1650 MW under the new 2800 MW RRS obligation.

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## **STUDY OBJECTIVE**

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## **BACKGROUND – LaaRs, GENERATION SPINNING RESERVES AND GENERATION GOVERNING**

Whenever generation is not in balance with the total demand, the electrical frequency of the entire interconnect will deviate from the nominal 60 Hz frequency at which the system was designed to operate. So the total generating capacity in a power system must be sufficient to supply the expected peak load demand plus a margin, or operating reserve. On a daily basis a system must carry enough operating reserves to regulate and to allow for unanticipated events, including forced outages and load forecast errors. Operating reserves are comprised of spinning reserves, non-spinning reserves, LaaRs, and DC tie-line response. Spinning reserves are generation operating at less than peak output, which are synchronized and immediately respond to frequency changes. LaaRs are loads that are tripped, either by frequency relaying or by operator action, to mitigate underfrequency events within the ERCOT system.

Responsive Reserves are a subset of operating reserves which ERCOT maintains to restore system frequency within the first few minutes of an event. Small load variations take place all the time, so frequency continuously deviates from 60 Hz. These smaller variations in frequency are covered by regulating reserve, which is made up of the portion of spinning reserve responsive to automatic generation control. These normal frequency deviations are quite small compared to those that occur following large disturbances. In addition to the considerable deviation in frequency from 60 Hz large disturbances can impose, an interconnected system will have natural system oscillations in frequency following a system

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disturbance. This oscillatory condition is normally damped in a large system but damped to a lesser extent, or even unstable, in a lightly loaded system with lower inertia. The focus of this study is the effect on the system response during the first 15 seconds following a large disturbance from varying two components of Responsive Reserves; spinning reserves and LaaRs. The particular group of LaaRs that are investigated in this study are those that are tripped by relaying within 30 cycles for system frequencies below a predetermined frequency set point, currently no less than 59.7 Hz in the ERCOT system

A key mechanism to spinning reserves is generator governing. Governing is the automatic response of the governor to a usually large change in frequency during the first 15 seconds following an event. Governing is the process where a generating unit changes its power output in response to a change in frequency. If the frequency drops below 60 Hz, governing will increase generation power output to arrest the frequency decline. Alternatively, if the frequency increases above 60 Hz, governing will decrease generation power output to arrest the frequency rise. For governing response to be effective, the following three elements must exist:

1. The unit must have a governing margin. If the unit is operating at full load, it cannot increase its output in response to a loss of generation. Similarly, a unit operating at 90% of full load cannot respond with 20% of its capacity to a loss of generation.
2. The unit's controls must permit governing. "turbine follow" and "sliding pressure control" for conventional steam plants, and operating combustion turbines on temperature control can effectively block governing action.
3. The unit must have a governor or speed input to the plant controls that is not blocked by intentional dead-bands or limiters.

The rate and magnitude of governor response to a speed change can be tuned for the characteristics of the generator that the governor controls and the power system to which it is connected.

## **STUDY METHODOLOGY**

### ***Software***

The Siemens PTI Power System Simulator for Engineering (PSSE) software was used for all simulations in this study.

### ***Models and Data***

#### **Network Model Data**

To capture the approximate ERCOT operating extremes, in terms of magnitude of load and generation, two network model cases were used as a starting point in the analysis; a summer peak case and a spring off-peak case.

The following summer peak case was used:

*08SUM1 -2008 SUMMER ON-PEAK BASE CASE - ERCOT ROS SSWG UPDATED  
08/31/2007 - ERCOT PSSE VER 30.3 CSC CONS. DISPATCH*

The following spring off-peak case was used:

**08SPG2 -2008 SPRING OFF-PEAK BASE CASE - ERCOT ROS SSWG UPDATED 11/28/2007 - ERCOT PSSE VER 30.3 CSC CONS. DISPATCH**

In each of the above two network cases, online non base load generating units and combined cycle trains from across the entire ERCOT system were selected for simulation of the spinning reserve portion of responsive reserves. These units are herein referred to as “participating units”. In order to meet the objectives of this study, it was necessary to simulate a range of LaaRs and corresponding generation spinning reserve combinations. This was facilitated by altering generation dispatch of various participating units, creating numerous variations of each of the two starting network cases. These network case variations are summarized in Tables 3 and 4. Details on LaaRs modeling is discussed in the “Dynamics Model Data” and “Study Approach” sections below.

**Table 3 – Network Case Variations Created For the Study, 2800 MW RRS**

NETWORK CASE	AMOUNT OF SPINNING RESERVE MODELED IN THE NETWORK CASE <sup>1</sup>		MIX OF SIMPLE CYCLE AND COMBINED CYCLE UNITS			
	% OF 2800 MW RRS	MW	SIMPLE CYCLE (MW)		COMBINED CYCLE (MW)	
			SUM	SPG	SUM	SPG
40% LaaRs	60	1680	1110	1039	570	641
45% LaaRs	55	1540	970	934	570	606
50% LaaRs	50	1400	913	812	487	588
55% LaaRs	45	1260	798	721	462	539
60% LaaRs	40	1120	704	673	416	447
65% LaaRs	35	980	589	570	391	410
70% LaaRs	30	840	520	494	320	346
75% LaaRs	25	700	397	393	303	307

**Table 4 – Network Case Variations Created For the Study, 2300 MW RRS**

NETWORK CASE	AMOUNT OF SPINNING RESERVE MODELED IN THE NETWORK CASE <sup>1</sup>		MIX OF SIMPLE CYCLE AND COMBINED CYCLE UNITS			
	% OF 2300 MW RRS	MW	SIMPLE CYCLE (MW)		COMBINED CYCLE (MW)	
			SUM	SPG	SUM	SPG
50% LaaRs	50	1150	789	618	361	532
55% LaaRs	45	1035	674	552	361	483
60% LaaRs	40	920	606	529	314	391
65% LaaRs	35	805	491	451	314	354
70% LaaRs	30	690	447	399	243	291
75% LaaRs	25	575	332	301	243	274

<sup>1</sup> In compliance with the ERCOT Operating Guide, all participating units are dispatched at no less than 80% of capability in all of the network cases used for this study. For participating combined cycle trains, all trains are dispatched at no less than 80% of capability.

## **Dynamics Model Data**

### ***Governor Models***

In the vast majority of the simulations performed for this study, governor models are used for the participating units while governor models are not used for the non-participating units. This effectively simulates the limitation of governor response to the participating units. While this is a conservative modeling approach for summer peak conditions, it was not intuitive whether or not this approach would be conservative for spring off-peak conditions. Therefore, a number of simulations were performed using the spring off-peak cases with governor models used for all on-line units. Details on the set-up for these simulations are provided in the sections that follow.

From previous comparisons of recorded frequency data following large disturbances within the ERCOT system to corresponding simulation results using “as-is” governor model data from the ERCOT Dynamics Model Database, it has been consistently demonstrated that the recorded frequency response does not match well with the simulated frequency response. Specifically, the ERCOT system has always been, in actuality, less responsive than the simulated ERCOT system. There have been a number of plausible explanations for these differences in response. Improvements in combined cycle governor modeling (combustion turbine and steam turbine governor models) over the last couple of years have significantly narrowed the gap between actual and simulated frequency response. However, more work is needed in this area to determine the remaining governor model inaccuracies and how to address them.

Given the discrepancy in recorded and simulated frequency response discussed above, the DWG realized some level of governor tuning would be necessary in order to produce sound results for this study. A method that was considered involved tuning governors on a unit basis utilizing unit specific power output data in response to actual events. In this way, unit specific characteristics, particularly whether or not the unit utilizes load control (runback), could be appropriately modeled. Because unit specific event data is not currently made available with corresponding system event data, this method proved to be infeasible.

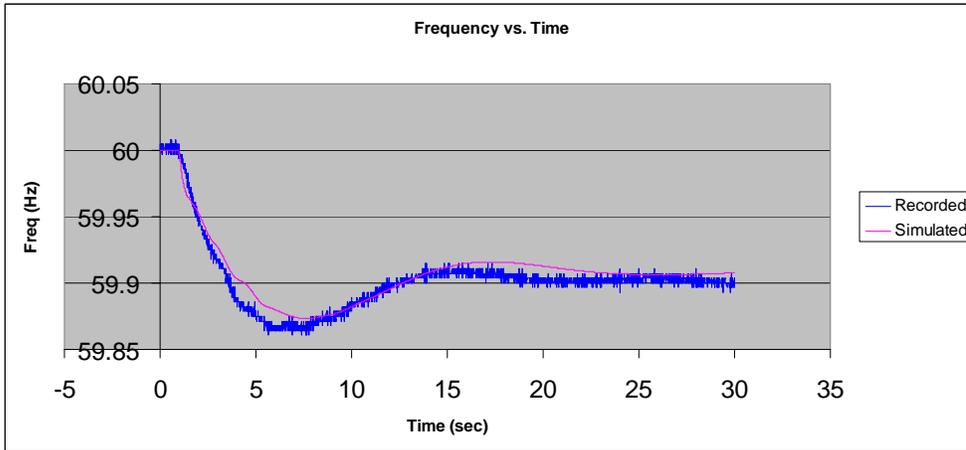
Alternatively, the DWG used a familiar governor tuning method used in previous DWG studies. As opposed to approximating the response of generating units on an individual basis, this method approximates the average response of generating units on an aggregate basis. The general steps for this method involved:

1. Choose a single governor model (or generic governor model) to replace the governor model for each simple cycle participating unit. Governor models for the participating units utilizing the new combined cycle governor models were not replaced with the generic governor model.
2. Adjust the droop and certain time constants of both the generic governor model and the combined cycle gas turbine governor model such that the simulated system frequency response for two or more known events approximates the recorded frequency response for those events.

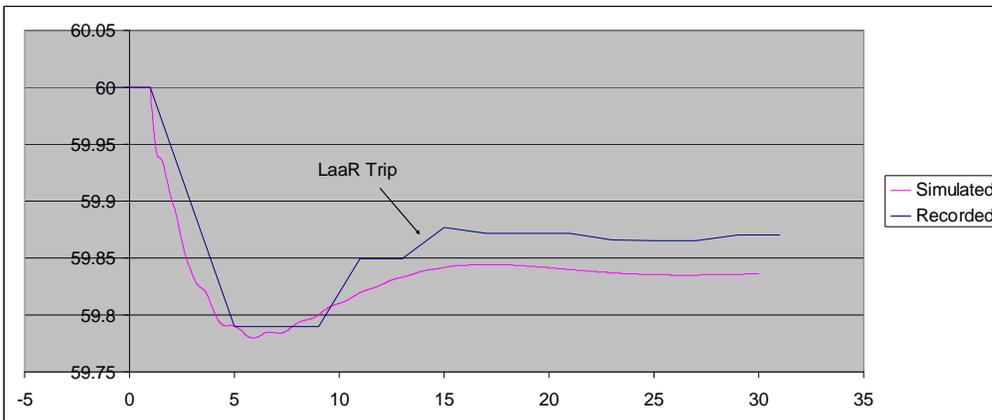
Because of its relative simplicity and common use within the ERCOT system, the IEESGO governor model from the Siemens PTI model library was selected for use as

the generic governor model. Although the tuning process turned out to be rather complex, event data from only two events was sufficient for obtaining tuned generic governor models. The 8/19/04 loss of the Forney plant and the 2/3/08 loss of Martin Lake 1 events were used. Both recorded and simulated frequencies for the Forney and Martin Lake events are shown in figures 1 and 2, respectively. The IEEEGO and combustion turbine governor model parameters used in this study are shown in figure 3.

**Figure 1 – 8/19/04 Forney Plant Trip, Recorded and Simulated Frequencies Using Tuned Governor Models**



**Figure 2 – 2/3/08 Loss of Martin Lake 1, Recorded and Simulated Frequencies Using Tuned Governor Models**



**Figure 3 – Final Generic Governor Model Parameters**

GENERIC GOVERNOR MODELS FOR USE IN THE DWG's 2008 RRS/LaaRs STUDY

IEESGO:

```
7004,'IEESGO', 1, 3.5000, 0, 0.0300, 0, 0, 0, 10.0000, 0, 0, 1.0000, 0.2857, /
```

Besides the appropriate bus number and unit ID changes, PMax and PMin will need to be set to match the corresponding network data values.

UCBGT and UCCPSS:

The only parameter changed in the UCBGT and UCCPSS models is the droop. In most, if not all, of the UCBGT and UCCPSS models, the droop was set at 5% in the starting DYR data. Tuning yielded a droop of 12.5%. In both the UCBGT and UCCPSS models, the droop is the first CON parameter. Below are samples of the tuned generic UCBGT and UCCPSS models:

```
1045,'USRMDL',1,'UCBGT',5,0,0,42,12,14,0.125,5.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.30000E-03,
0.50000E-02,0.10000,0.10000E-01,10.000,2.0000,0.0000,0.10000,0.0000,10.000,1.0000,0.20000,1.0000,
0.15000,0.91700,2.5000,10.000,15.000,0.50000,1.0000,0.0000,1.0000,0.25000,1.5000,1.0000,0.0000,
1.5000,0.50000,0.9500,0.95575,1.0000,1.0010,1.0500,0.97568,80.,/ Cal Energy - Power Resources GT1
```

```
1937,'USRMDL',5,'UCCPSS',5,0,0,67,16,21,0.125,5.0000,0.0000,0.0000,0.0000,0.0000,0.30000E-03,
0.50000E-02,0.10000,0.10000E-01,10.000,2.0000,0.0000,0.10000,0.0000,10.000,1.0000,0.20000,1.0000,
0.15000,0.91700,2.5000,10.000,15.000,0.50000,1.0000,0.0000,1.0000,0.25000,1.5000,1.0000,0.0000,
1.5000,0.50000,0.9500,0.95575,1.0000,1.0010,1.0500,0.97568,180.00,0.10000,0.0000,1.0000,1.0000,
0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,300.00,0.15000,0.50000,10.000,
2.0000,3.0000,10.000,0.0000,0.0000,0.20000,88,/ Midlothian - SS5
```

### ***LaaR Modeling***

For dynamic simulations, the simulation of automatic LaaR tripping is accomplished through the use of an underfrequency load shedding model. The desired frequency trip setting, trip delay, and breaker operate time is entered into the model for any particular load or group of loads. In this study, there were a myriad of LaaR model configurations utilized to establish the set-up for:

1. Various LaaR and spinning reserve combinations analyzed,
2. Various LaaR locations analyzed,
3. Various LaaR frequency trip points analyzed, and
4. Various LaaR trip delays analyzed.

The specific LaaR configurations used in this study are outlined in the “Study Approach” section below.

### ***Low Set Underfrequency Relay Modeling***

Section 2.9 of the ERCOT Operating Guide requires at least 25% of the ERCOT system load that is not equipped with high set underfrequency relaying (LaaRs) to be equipped with automatic underfrequency relaying. The firm load shed amounts and corresponding frequency thresholds are as follows:

- 5% of the ERCOT system firm load at no less than 59.3 Hz.
- An additional 10% of the ERCOT system firm load, for a total of 15%, at no less than 58.9 Hz.
- An additional 10% of the ERCOT system firm load, for a total of 25%, at no less than 58.5 Hz.

Considering the capacity of the largest single ERCOT generating plant (2500 MW), the amount of RRS being simulated (2300 MW and 2800 MW), along with previous experience simulating frequency events in the ERCOT system, the DWG did not expect to see system frequencies at or below 59.3 Hz from the simulations for this

study. Accordingly, the approach taken with regard to underfrequency firm load shed modeling was to add such relay modeling as needed.

**Load Modeling**

Dynamic simulation applications model the sensitivity of loads to changes in voltages via the “ZIP” model, shown below:

$$P = P_0 \left( p_1 \left( \frac{V}{V_0} \right)^2 + p_2 \left( \frac{V}{V_0} \right) + p_3 \right) \quad Q = Q_0 \left( q_1 \left( \frac{V}{V_0} \right)^2 + q_2 \left( \frac{V}{V_0} \right) + q_3 \right)$$

Where,

$P_0$  = Initial real power

$Q_0$  = Initial reactive power

$V_0$  = Initial bus voltage

$p_1$  = Fraction of  $P_0$  for which resistance is constant

$q_1$  = Fraction of  $Q_0$  for which reactance is constant

$p_2$  = Fraction of  $P_0$  for which current is constant

$q_2$  = Fraction of  $Q_0$  for which current is constant

$p_3$  = Fraction of  $P_0$  that is constant

$q_3$  = Fraction of  $Q_0$  that is constant

$P$  = Real power at a given time step

$Q$  = Reactive power at the time step

$V$  = Bus voltage at the time step

The factors used in the ZIP model ( $p_1$ ,  $p_2$ ,  $p_3$ ,  $q_1$ ,  $q_2$ , and  $q_3$ ) for ERCOT loads in this study are based on a 1980’s study conducted by the University of Texas at Arlington (UTA). The ERCOT ZIP model components are shown in table 5.

**Table 5 - ZIP Model Components Used in ERCOT**

COMPANY	REAL POWER COMPONENTS		REACTIVE POWER COMPONENTS	
	$p_1$	$p_2$	$q_1$	$q_3$
Oncor	56	44	50	50
Centerpoint	50	50	50	50
CPS	80	20	50	50
AEP (WTU)	41	59	50	50
LCRA	50	50	50	50
AE	50	50	50	50
AEP (CPL)	50	50	50	50
BEC	79	21	50	50
TMPA	79	21	50	50
TNMP <sup>2</sup>	50	50	50	50
STEC	79	21	50	50

<sup>2</sup> The TNMP loads were not part of the UTA research project. Typical characteristics for the TNMP loads were used in this study.

The sensitivity of loads to changes in frequency were modeled via the Siemens PTI library model “LDFRAL”, as shown below:

$0, 'LDFRAL', **, m, n, r, s$

The model “LDFRAL” modifies the “ZIP” model for all buses in the network model in the following way:

$$P = P_0 \left( p_1 \left( \frac{V}{V_0} \right)^2 + p_2 \left( \frac{V}{V_0} \right) \left( \frac{\omega}{\omega_0} \right)^r + p_3 \left( \frac{\omega}{\omega_0} \right)^m \right)$$

$$Q = Q_0 \left( q_1 \left( \frac{V}{V_0} \right)^2 + q_2 \left( \frac{V}{V_0} \right) \left( \frac{\omega}{\omega_0} \right)^s + q_3 \left( \frac{\omega}{\omega_0} \right)^n \right)$$

Where,

$m$  = Constant real power load exponent

$n$  = Constant reactive power load exponent

$r$  = Constant real load current exponent

$s$  = Constant imaginary load current exponent

$\omega_0$  = Initial bus frequency

$\omega$  = Bus frequency at a given time step

As in all dynamic studies performed for the ERCOT system in the past, the specific “LDFRAL” model used in this study is as follows:

$0, 'LDFRAL', **, 0, 2.0, 0, 0$

### **Wind Generation Modeling**

The focal point of this study is the system frequency response within the first 20-30 seconds following loss of generation. Since wind plant generation is non-synchronous, the dynamic characteristics of wind turbines have no significant impact on system frequency response following loss of generation elsewhere as long as most, or all of the wind generation remains online and the wind generation electrical output remains approximately constant over the 20-30 second study interval. The only considerable effect wind plant generation can have on system frequency response in this study occurs when the electrical output of wind turbines changes abruptly over the study interval. For the purposes of this study, abrupt changes in wind plant electrical output arise when wind turbines trip offline due to either frequency or voltage deviations at the terminals of the wind turbine generators beyond thresholds corresponding to the wind turbine generator over/under frequency and over/under voltage relay settings. Therefore, the DWG’s approach to wind modeling in this study was to monitor voltage and frequency at all wind plant buses in the simulations and include loss of wind turbine electrical power output in the simulations only as needed.

## Study Approach

### Simulation Plan

The spinning reserve and LaaRs components of 2300 MW and 2800 MW RRS are varied in this study to identify thresholds where reliability concerns emerge. There are, of course, numerous other related variables that must be taken into account. The sensitivities between many of the other variables and power system electrical quantities such as frequency and voltage were not intuitive and, therefore, needed to be simulated. The power system variables analyzed in this study are summarized in Tables 6 and 7.

**Table 6 – Power System Variables Analyzed, 2800 MW RRS**

VARIABLE	COMMENTS
Amount of LaaRs	Varied between 40% and 75% of 2800 MW RRS. Sum of LaaRs and spinning reserve held at 2800 MW for all simulations.
Amount of spinning reserve/Generator governor response.	<ul style="list-style-type: none"> <li>- Governor response allowed for only participating units in most of the simulations. In those cases, varied spinning reserve between 25% and 60% of 2800 MW RRS. Sum of LaaRs and spinning reserve held at 2800 MW for these simulations.</li> <li>- Sensitivity runs were conducted with governor response from all on-line generating units.</li> </ul>
Amount of generation tripped	Varied between 500 MW and 2500 MW.
Location of generation tripped	Varied between Comanche Peak and South Texas Project.
Location of LaaRs	<ol style="list-style-type: none"> <li>(1) Existing locations (approximately 80% along the Gulf Coast, remaining spread approximately even throughout remainder of Texas).</li> <li>(2) Distributed uniformly across the following areas:               <ol style="list-style-type: none"> <li>a. Entire ERCOT system.</li> <li>b. West Texas CSC zone.</li> <li>c. North Texas CSC zone.</li> <li>d. Houston CSC zone.</li> <li>e. South Texas CSC zone.</li> </ol> </li> </ol>
LaaR relay trip settings	<p><b>59.7 Hz Tier</b></p> <ol style="list-style-type: none"> <li>(1) For existing LaaR locations, used existing LaaR relay trip settings.</li> <li>(2) For all other LaaR locations, varied between 59.7 and 59.78 Hz.</li> </ol> <p><b>59.8 Hz Tier</b></p> <p>Varied between 59.8 and 59.88 Hz.</p>
LaaR relay trip delays	Varied between 0 cycles and 20 cycles.

**Table 7 – Power System Variables Analyzed, 2300 MW RRS**

VARIABLE	COMMENTS
Amount of LaaRs	Varied between 50% and 75% of 2300 MW RRS. Sum of LaaRs and spinning reserve held at 2300 MW for all simulations.
Amount of spinning reserve/Generator governor response.	Governor response allowed for only participating units in all simulations. Varied spinning reserve between 25% and 50% of 2300 MW RRS. Sum of LaaRs and spinning reserve held at 2300 MW for all simulations.
Amount of generation tripped	Varied between 300 MW and 1250 MW.
Location of generation tripped	Varied between Comanche Peak and South Texas Project.
Location of LaaRs	(1) Existing locations (approximately 80% along the Gulf Coast, remaining spread approximately even throughout remainder of Texas). (2) Distributed uniformly across the following areas: <ol style="list-style-type: none"> <li>a. Entire ERCOT system.</li> <li>b. West Texas CSC zone.</li> <li>c. North Texas CSC zone.</li> <li>d. Houston CSC zone.</li> <li>e. South Texas CSC zone.</li> </ol>
LaaR relay trip settings	(1) For existing LaaR locations, used existing LaaR relay trip settings. (2) For all other LaaR locations, varied between 59.7 and 59.78 Hz.

The simulations performed in this study were arranged with the goal of producing results that would be applicable to any operating scenario in the ERCOT system. Accordingly, the simulations were designed to identify the worst case conditions for tripping LaaRs in the ERCOT system and the subsequent limits on the amount of LaaRs that can be reliably deployed. The simulations performed in this study are summarized in Tables 8 and 9.

**Table 8 – Summary of Simulations, 2800 MW RRS**

SERIES	NETWORK CASE	LaaR CONFIGURATION					SPINNING RESERVE (MW)	GENERATION TRIPPED		NUMBER OF SIMULATIONS
		AMOUNT (% of 2800 MW)	LOCATION	TRIP SETTING (Hz)	TRIP DELAY (cycles)	BREAKER OPERATE TIME (cycles)		AMOUNT (MW)	LOCATION	
1	SP	50-75	EXIST	EXIST	15	5	1400-700	2500	STP	6
2	SP	50-75	EXIST	EXIST	15	5	1400-700	2300	CP	6
3	SOP	65-75	EXIST	EXIST	15	5	980-700	900-1150	CP	18
4	SOP	65	EE	59.70	15	5-15	980	900-1150	CP	18
5	SOP	50-65	EE	59.70-59.78	15	5	1400-980	500-1000	CP	120
6	SOP	50-65	EXIST	EXIST	15	5	1400-980	500-1000	CP	24
7	SOP	50-60	WTX	59.70-59.74	15	5	1400-1120	500-1000	CP	54
8	SOP	50-60	NTX	59.70-59.74	15	5	1400-1120	500-1000	CP	54
9	SOP	50-60	HOU	59.70-59.74	15	5	1400-1120	500-1000	CP	54
10	SOP	50-60	STX	59.70-59.74	15	5	1400-1120	500-1000	CP	54
11	SOP	50-60	EXIST & WTX	EXIST & 59.70-59.74	15	5	1400-1120	500-1000	CP	54
12	SOP	50-60	EXIST & NTX	EXIST & 59.70-59.74	15	5	1400-1120	500-1000	CP	54
13	SOP	50-60	EXIST & HOU	EXIST & 59.70-59.74	15	5	1400-1120	500-1000	CP	54
14	SOP	50-60	EXIST & STX	EXIST & 59.70-59.74	15	5	1400-1120	500-1000	CP	54
15	SOP	50-60	WTX	59.70-59.74	15	5	1400-1120	500-1000	STP	54
16	SOP	50-60	NTX	59.70-59.74	15	5	1400-1120	500-1000	STP	54
17	SOP	50-60	HOU	59.70-59.74	15	5	1400-1120	500-1000	STP	54
18	SOP	50-60	STX	59.70-59.74	15	5	1400-1120	500-1000	STP	54
19	SOP	50-60	WTX	59.70-59.74	15	5	10011-10466	500-1000	STP	54
20	SOP	50-60	NTX	59.70-59.74	15	5	10011-10466	500-1000	STP	54
21	SOP	50-60	HOU	59.70-59.74	15	5	10011-10466	500-1000	STP	54
22	SOP	50-60	STX	59.70-59.74	15	5	10011-10466	500-1000	STP	54
23	SOP	50-60	WTX	59.70-59.74	0-10	5	1400-1120	500-1000	STP	162
24	SOP	50-60	NTX	59.70-59.74	0-10	5	1400-1120	500-1000	STP	162
25	SOP	50-60	HOU	59.70-59.74	0-10	5	1400-1120	500-1000	STP	162

SERIES	NETWORK CASE	LaaR CONFIGURATION					SPINNING RESERVE (MW)	GENERATION TRIPPED		NUMBER OF SIMULATIONS
		AMOUNT (% of 2800 MW)	LOCATION	TRIP SETTING (Hz)	TRIP DELAY (cycles)	BREAKER OPERATE TIME (cycles)		AMOUNT (MW)	LOCATION	
26	SOP	50-60	STX	59.70-59.74	0-10	5	1400-1120	500-1000	STP	162
27	SOP	50-60	WTX	59.70-59.74	20	5	1400-1120	500-1000	STP	54
28	SOP	50-60	NTX	59.70-59.74	20	5	1400-1120	500-1000	STP	54
29	SOP	50-60	HOU	59.70-59.74	20	5	1400-1120	500-1000	STP	54
30	SOP	50-60	STX	59.70-59.74	20	5	1400-1120	500-1000	STP	54
31	SOP	55	EE	59.74	15	5	1120-700	500-1250	STP	180
		60-75		59.80-59.88						
32	SOP	50	WTX	59.72	15	5	1260-700	500-1250	STP	225
		55-75		59.80-59.88						
33	SOP	55	NTX	59.72	15	5	1120-700	500-1250	STP	180
		60-75		59.80-59.88						
34	SOP	50	HOU	59.74	15	5	1260-700	500-1250	STP	225
		55-75		59.80-59.88						
35	SOP	55	STX	59.72	15	5	1120-700	500-1250	STP	180
		60-75		59.80-59.88						
36	SOP	50-75	EXIST	MEXIST	15	5	1400-700	500-1250	STP	63
37	SOP	50-75	EXIST	59.70-59.78	15	5	1400-700	500-1250	STP	270

Note 1:  
 SP = Summer Peak  
 SOP = Spring Off-Peak

Note 2:  
 EXIST = Located at existing contracted locations  
 EE = Uniformly over entire ERCOT system  
 WTX = Uniformly over West Texas CSC zone  
 NTX = Uniformly over North Texas CSC zone  
 HOU = Uniformly over Houston CSC zone  
 STX = Uniformly over South Texas CSC zone  
 EXIST & WTX = 50% of 2300 MW at existing contracted locations with remaining uniformly over West Texas CSC zone  
 EXIST & NTX = 50% of 2300 MW at existing contracted locations with remaining uniformly over North Texas CSC zone  
 EXIST & HOU = 50% of 2300 MW at existing contracted locations with remaining uniformly over Houston CSC zone  
 EXIST & STX = 50% of 2300 MW at existing contracted locations with remaining uniformly over South Texas CSC zone

Note 3:  
 EXIST = Tripped at existing relay trip set-points. 9.1% of LaaRs tripped at 59.8 Hz, 0.9% at 59.72 Hz, 1.4% between 59.71 and 59.72 Hz, 10.7% at 59.71 Hz, 25.4% between 59.70 and 59.71 Hz, 52.5% at 59.7 Hz.  
 MEXIST = Modified version of existing relay trip set-points. 0.9% LaaRs tripped at 59.72 Hz, 1.4% between 59.71 and 59.72 Hz, 10.7% at 59.71 Hz, 25.4% between 59.70 and 59.71 Hz, 61.6% at 59.7 Hz.

Note 4:  
 STP = South Texas Project  
 CP = Comanche Peak

**Table 9 – Summary of Simulations, 2300 MW RRS**

SERIES	NETWORK CASE	LaaR CONFIGURATION					SPINNING RESERVE (MW)	GENERATION TRIPPED		NUMBER OF SIMULATIONS
		AMOUNT (% of 2300 MW)	LOCATION	TRIP SETTING (Hz)	TRIP DELAY (cycles)	BREAKER OPERATE TIME (cycles)		AMOUNT (MW)	LOCATION	
38	SOP	50-75	EXIST	EXIST	15	5	1150-575	900-1150	CP	36
39	SOP	50-75	EXIST	MEXIST	15	5	1150-575	500-1250	STP	54
40	SOP	50-75	EXIST	59.70-59.78	15	5	1150-575	500-1250	STP	270
41	SOP	50-65	EE	59.70-59.78	15	5	1150-805	300-1000	CP	160
42	SOP	50-65	WTX	59.70-59.78	15	5	1150-805	300-1000	STP	160
43	SOP	50-65	NTX	59.70-59.78	15	5	1150-805	300-1000	STP	160
44	SOP	50-65	HOU	59.70-59.78	15	5	1150-805	300-1000	STP	160
45	SOP	50-65	STX	59.70-59.78	15	5	1150-805	300-1000	STP	160
<p>Note 1: SOP = Spring Off-Peak</p> <p>Note 2: EXIST = Located at existing contracted locations EE = Uniformly over entire ERCOT system WTX = Uniformly over West Texas CSC zone NTX = Uniformly over North Texas CSC zone HOU = Uniformly over Houston CSC zone STX = Uniformly over South Texas CSC zone</p> <p>Note 3: EXIST = Tripped at existing relay trip set-points. 9.1% of LaaRs tripped at 59.8 Hz, 0.9% at 59.72 Hz, 1.4% between 59.71 and 59.72 Hz, 10.7% at 59.71 Hz, 25.4% between 59.70 and 59.71 Hz, and 52.5% at 59.7 Hz. MEXIST = Modified version of existing relay trip set-points. 0.9% LaaRs tripped at 59.72 Hz, 1.4% between 59.71 and 59.72 Hz, 10.7% at 59.71 Hz, 25.4% between 59.70 and 59.71 Hz, and 61.6% at 59.7 Hz.</p> <p>Note 4: STP = South Texas Project CP = Comanche Peak</p>										

**Other Simulation Details**

The following output channels were included for all simulations:

1. Frequency and voltage at the Jewett 345 kV bus.
2. Bus voltage angle statistic channels.
3. Rotor angles for all machines.
4. Complex power for all machines.
5. Terminal voltage for all machines.
6. Field voltage for all machines.
7. Various power statistics for all areas and zones.
8. Frequency and voltage at all wind plants.

A 30 second simulation period was used for all simulations.

### **Study Criteria**

There were several criteria used in the interpretation of the study results.

1. System stability – For a scenario to be considered acceptable, there must be no abnormal system conditions such as machines out-of-step.
2. Underfrequency limit – As described in the above section on low set underfrequency load shed relay modeling, initial runs were conducted without such relays modeled. The underfrequency limit for all of these initial runs was 59.3 Hz. This limit was used only as a threshold to model underfrequency firm load shed as needed.
3. Overfrequency limit (frequency overshoot) – The maximum operating frequency for a power system is a function of numerous factors, the most notable of which are related to how the major components of generating plants are affected by overfrequency. The overfrequency limit of any power system, in terms of both frequency and duration of overfrequency, is most likely to be established by the overfrequency relaying protecting certain power plant components. Because the capabilities of generating plant equipment varies widely, there are no national standards that establish limits related to overfrequency ride-through for relaying at generating plants. However, some reliability organizations do establish such limits. For instance, the Western Electricity Coordinating Council requires the following with regard to generator overfrequency relaying<sup>3</sup>:
  - Continuous operation for frequencies between 60 Hz and 60.6 Hz
  - Minimum trip time of 3 minutes for frequencies  $\geq$  60.6 Hz.
  - Minimum trip time of 30 seconds for frequencies  $\geq$  61.6 Hz.
  - Instantaneous trip allowed for frequencies above 61.7 Hz.

In the absence of such limits for the ERCOT system, the DWG selected 60.4 Hz as the overfrequency limit for this study. The 60.4 Hz overfrequency criterion is a conservative limit used in the responsive reserve study conducted by the DWG in 2002. Increasing the overfrequency limit above 60.4 Hz should not be done without coordination with plant operators and a detailed study of plant equipment in the ERCOT system.

4. Wind plant voltage and frequency – Voltage and frequency were monitored at all wind plant buses in order to properly model any loss of wind plant generation due to under/over voltage and/or under/over frequency conditions. Wind generator voltage relaying is typically set for continuous operation between 90% and 110% of nominal voltage. For loss of wind generation to occur due to a voltage issue within the 30 second simulation interval used in this study, wind generator terminal voltage would typically need to drop to about 30% or rise above about 110% of nominal voltage. Wind generator frequency relaying is typically set such that the unit can operate continuously between about 57 Hz and 62 Hz. For frequencies outside of that

<sup>3</sup> “WECC Coordinated Off-Nominal Frequency Load Shedding and Restoration Requirements”, July 2005.

band, the frequency relaying typically trips instantaneously. Subsequently, the following voltage and frequency criteria were used for all wind plant buses to determine the need for modeling loss of wind plant generation:

- Undervoltage limit of 30% of nominal.
- Overvoltage limit of 110% of nominal
- Underfrequency limit of 57 Hz.
- Overfrequency limit of 62 Hz.

## **STUDY RESULTS**

### ***Summer Peak Conditions, 2800 MW RRS***

During peak loading conditions, system inertia is at or near peak levels. Therefore, frequency overshoot following tripping of LaaRs during the summer peak was either not expected to be excessive or not expected to occur. The series 1 and 2 simulations sufficiently confirm these expectations. No frequency overshoot occurs in any of the summer peak scenarios. The minimum frequency drop, about 59.63 Hz, occurred for 2500 MW loss of the STP plant with the minimum amount of LaaRs simulated (50% of 2800 MW, or 1400 MW).

### ***Spring Off-Peak Conditions, 2800 MW RRS***

Since system inertia is the lowest during off-peak loading, the Spring off-peak scenarios are the critical cases for frequency overshoot. The following paragraphs summarize the series 3-35 Spring off-peak simulations and results.

#### **Series 3**

In the first series of simulations for the Spring off-peak case, existing LaaR relay locations and corresponding trip settings are modeled to screen out the larger percentages of LaaRs that would result in excessive frequency overshoot. Overshoot violations occur with LaaRs percentages greater than 65% when the amount of generation lost is in the range of 1000 – 1050 MW.

#### **Series 4**

In the series 4 simulations, LaaRs are held at 65% while the LaaR breaker operate times were varied. Furthermore, two additional aspects of the LaaR data were varied moving from the series 3 to series 4 simulations. The first was the LaaR locations. In the series 4 simulations, all of the LaaRs are spread uniformly across the entire ERCOT system. The second was the LaaR trip settings. All LaaRs were set to trip at 59.7 Hz in series 4.

The series 4 plots indicate the variance of breaker operate times have no bearing on frequency response. Although there were no frequency overshoot violations in the series 4 runs, the series 4 plots reveal two other important details.

1. There is an upward trend in frequency overshoot as the amount of generation tripped is varied towards the minimum simulated 900 MW.
2. The series 3 simulations did not show an upward trend in frequency overshoot as the amount of generation tripped is decreased. This is because existing LaaR relay

data is used in the series 3 runs. The trip levels in the existing LaaR data is such that approximately 9% of the total LaaRs trips at 59.8 Hz, 1% LaaRs trips at 59.72 Hz, and the remaining LaaRs trips at frequencies between 59.7 and 59.72 Hz. Having the LaaRs spread out over a range of frequencies, particularly having 9% of the LaaRs tripping at 59.8 Hz and all of the remaining LaaRs tripping at 59.72 or less, effectively blunts frequency overshoot. This critical detail supports the notion that existing LaaR data should not be used to determine LaaRs limits applicable in a general sense. While the existing LaaR data may be realistic for the present, the existing LaaR data may not always be applicable.

Based on these two observations, most of the successive runs test system frequency response from tripping all LaaRs at the same frequency following loss of generation less than 900 MW.

### **Series 5**

Results from the series 5 runs support conclusions made from comparison of the series 3 and 4 results. In this series LaaRs percentages above 55%, as well as 55% LaaRs tripped above 59.74 Hz, result in frequency overshoot violations.

### **Series 6**

The purpose of the series 6 runs was to have another means of verifying the conclusion made from the series 3 and series 4 runs that use of the existing LaaR data produces optimistic results. The only modeling detail changed going from the series 5 runs to the series 6 runs was the use of existing LaaR data. Results from the series 6 runs confirm the aforementioned conclusion. There were no frequency overshoot violations in the series 6 runs.

### **Series 7-10**

In all of the previous simulations, the geographical nature of the LaaRs was such that either the LaaRs were distributed uniformly throughout the entire ERCOT system or the existing LaaR geographical distribution was modeled. The purpose of the series 7-10 simulations was to determine the relationship, if any, between system frequency response and location of LaaRs and, assuming a measurable relationship exists, to determine whether or not the series 5 runs were the worst case scenario in terms of LaaR geographical locations. All LaaRs were distributed uniformly in the West Texas, North Texas, Houston, and South Texas Commercially Significant Constraint (CSC) zones in the series 7, 8, 9, and 10 runs, respectively. The following LaaRs percentages resulted in frequency overshoot violations in the series 7-10 runs:

- 55% or greater when located in the West Texas CSC zone.
- Greater than 55% when located in the North Texas CSC zone.
- 55% or greater when located in the Houston CSC zone.
- Greater than 55% when located in the South Texas CSC zone.

Comparing the series 7-10 results to the series 5 results, there is a small sensitivity of frequency overshoot to the geographical locations of LaaRs. Having the LaaRs distributed uniformly throughout the ERCOT system presents a slightly more optimistic scenario than confining the LaaRs to the various CSC zones.

**Series 11-14**

The purpose for the series 11-14 runs was to examine the present-day situation of adding additional LaaRs to the existing LaaR pool. Existing LaaRs totaling 50% of 2300 MW, or 1150 MW, are modeled in all of the runs. Additional LaaRs needed for modeling 55%-60% LaaRs are lumped in the West Texas, North Texas, Houston, and South Texas CSC zones in the series 11, 12, 13, and 14 runs, respectively. The series 11-14 runs further verify the conclusion that the frequency trip settings in the existing LaaR data yield optimistic results that should not be used to determine LaaR limits in a general sense. Again, about 9% of the existing LaaRs is tripped at 59.8 Hz and the remaining existing LaaR is tripped at or below 59.72 Hz. Subsequently, there were no frequency overshoot violations in the series 11-14 results.

**Series 15-18**

In the series 3-14 simulations, loss of generation at the Comanche Peak plant was simulated. Although the inertia of the two Comanche Peak generating units are relatively high, the inertia of these two units are not the highest within the ERCOT system. The two generating units at South Texas Project (STP) have the highest inertia within the ERCOT system. The purpose of the series 15-18 runs was to examine how the results of the series 7-10 runs would be affected by simulating loss of the higher inertia generation at STP. The series 15-18 results show tripping STP generation presents more restrictive LaaR limits than identified in the previous simulations where Comanche Peak generation was tripped. The following LaaRs percentages and associated frequency trip levels resulted in frequency overshoot violations in the series 15-18 runs:

- Greater than 50% and 50% tripped at greater than 59.72 Hz when located in the West Texas CSC zone.
- Greater than 55% and 55% tripped at greater than 59.72 Hz when located in the North Texas CSC zone.
- Greater than 50% and 50% tripped at greater than 59.74++<sup>4</sup> Hz when located in the Houston CSC zone.
- Greater than 55% and 55% tripped at greater than 59.72 Hz when located in the South Texas CSC zone.

**Series 19-22**

In the series 3-18 runs, the only generating units responding following loss of generation were the units participating in the responsive reserve service. The series 19-22 runs test the effect of response from all available units in the ERCOT system. The series 19-22 runs are effectively the series 15-18 runs with the original governor models included for all units not participating in the responsive reserve service. As the series 19-22 results indicate, having additional governor response outside from that of the spinning reserve units lessens frequency overshoot to a great extent. The primary reason for this is the additional generator governor action reduces the rate of frequency decline following loss of generation, reducing the amount of LaaRs that trip. There were no frequency overshoot violations in the series 19-22 runs.

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<sup>4</sup> The highest LaaR trip level simulated in these runs was 59.74 Hz. The actual threshold is somewhat higher than 59.74 Hz.

**Series 23-30**

The LaaR relay delay time was simulated at 15 cycles in all of the previous simulations. The purpose of the series 23-30 runs was to test the effect of varying LaaR trip delays in the series 15-18 runs. In these runs, the LaaR trip delays were varied between 0 cycles (instantaneous trip) and 20 cycles. The series 23-30 results show, for the most part, changes in LaaR relay trip delays have no effect on system frequency performance. The exception to this is a few of the scenarios where all of the LaaRs are located in the South Texas CSC zone. The following LaaRs percentages resulted in frequency overshoot violations in the series 23-30 runs that were not already identified in the series 15-18 runs:

- Greater than 50% when located in the South Texas CSC zone.

**Series 31-35**

The series 31-35 runs test the deployment of LaaRs in two tiers. The first tier is the same “59.7 Hz” tier studied in the series 1-30 runs. The second tier is a “59.8 Hz” tier. The assumption made in these runs is the amount of LaaRs at the first tier and the corresponding first tier trip levels are held at the applicable threshold identified from the series 5 simulations (setup for series 31 runs) and series 15-18 simulations (setup for series 32-35 runs). There are two key observations from the series 31-35 results:

1. Tiers of LaaRs above the first LaaRs tier cannot be reliably deployed when the first tier LaaRs are operated at threshold levels.

In the set-up for the series 32, 33, and 35 runs, the first tier LaaRs are operated at threshold levels. That is, the amount of first tier LaaRs is at a critical level and all first tier LaaRs tripping is done at the same critical frequency. All levels of second tier LaaR tripping resulted in excessive frequency overshoot in the series 32, 33, and 35 runs.

2. Tiers of LaaRs above the first LaaRs tier can be reliably deployed when the first tier LaaRs are operated within critical levels. The maximum amount and maximum tripping level of higher tier LaaRs is a function of how far within critical levels the first tier LaaRs are limited.

In the set-up for the series 31 runs, the first tier LaaRs are modeled to operate somewhat below actual threshold levels. The amount of first tier LaaRs and tripping frequency used in the series 31 runs are established from thresholds derived from the series 5 runs (55% LaaRs, all tripped at 59.74 Hz). It can be concluded from comparison of the various series 5 plots that the LaaRs threshold tripping frequency for the series 5 runs is actually somewhere between 59.74 and 59.76 Hz. Consequently, the series 31 results indicate second tier LaaRs can be deployed in the following ways:

- Up to 5% tripped between 59.82 Hz and 59.8 Hz.
- Up to 15% tripped at no more than 59.8 Hz.

The same situation exists for the series 34 runs. The first tier LaaRs for the series 34 runs are also modeled to operate below actual threshold levels. The first tier LaaR thresholds used in the series 34 runs are based on thresholds

defined in the series 17 runs (50% LaaRs, all tripped at 59.74 Hz). The actual threshold is slightly above 59.74 Hz. Consequently, the series 34 results indicate up to 5% second tier LaaRs, tripped at no more than 59.8 Hz, can be reliably deployed.

### **Series 36**

The series 3 runs provide meaningful results for the consideration of the amount of LaaRs that can be reliably deployed assuming the LaaR frequency set-points remain very similar to that of existing LaaRs wherein the LaaRs trip over a range of frequencies between 59.7 Hz and 59.78 Hz. Recall the following points from the above discussion on the series 3 and series 4 simulation results:

1. The series 3 runs suggest up to 65% of 2800 MW LaaRs could be reliably deployed assuming the LaaRs maintained a trip frequency and geographic location profile very similar to that of the existing LaaR pool.
2. From the comparison between the series 3 and series 4 results, the existing LaaR relay frequency set-points produce results that are optimistic relative to scenarios where there exists a tighter band of trip frequencies among the LaaR relays.
3. About 9% of the LaaRs modeled in the series 3 simulations trip at 59.8 Hz.

The purpose of the series 36 runs was to quantify how much the 65% max LaaRs number would decrease when the relay trip set-point of the 9% LaaRs, set to trip at 59.8 Hz in the series 3 runs, was changed to a lower frequency. Specifically, the relay trip set-point for the 9% LaaRs was changed from 59.8 Hz to 59.70 Hz in the series 36 runs. Plots from the series 36 runs indicate that frequency overshoot violations will occur with LaaRs percentages greater than 60%.

### **Series 37**

The series 37 runs build on the series 36 runs. The purpose of the series 37 runs was to identify the maximum allowable amount of LaaRs, assuming the geographical locations of the LaaRs are similar to that of the existing LaaR pool, when all of the LaaRs trip at the same frequency. The series 37 runs essentially identify the worst case scenario for tripping LaaRs when the geographical locations of the LaaRs are similar to that of the existing LaaR pool. Results from the series 37 runs demonstrate that up to 55% of 2800 MW LaaRs, geographically distributed similar to the existing LaaR pool, can be reliably deployed with all of the LaaRs set to trip at no more than 59.72 Hz.

### ***Spring Off-Peak Conditions, 2300 MW RRS***

The purpose of the series 38-45 runs was to identify LaaRs amounts that can be reliably deployed at the 2300 MW level. Therefore, the series 38-45 runs are essentially the definitive series of runs from the 2800 MW RRS series 3-37 runs repeated at 2300 MW RRS. The series 38-45 runs indicate that the amount of LaaRs, as a percentage of the total RRS, reliably deployable at the 2300 MW RRS level is generally a bit higher than that at the 2800 MW RRS level.

**Series 38**

The series 38 runs are analogous to the series 3 runs wherein the LaaRs limit was identified at 65% of 2800 MW RRS with the LaaRs at the existing locations and corresponding existing trip settings. The series 38 runs indicate the LaaRs limit is 70% of 2300 MW RRS.

**Series 39**

The series 39 runs are analogous to the series 36 runs wherein the LaaRs limit was identified at 60% of 2800 MW RRS with the LaaRs at the existing locations, but with a modified version of the existing relay trip settings. The series 39 runs indicate the LaaRs limit is 65% of 2300 MW RRS.

**Series 40**

The series 40 runs are analogous to the series 37 runs wherein the LaaRs limit was identified at 55% of 2800 MW RRS with the LaaRs at the existing locations, but with all of the LaaRs tripping at the same frequency. The corresponding maximum trip frequency was 59.72 Hz. The series 40 runs indicate the LaaRs limit is 60% of 2300 MW RRS with a 59.74 Hz maximum trip frequency.

**Series 41**

The series 41 runs are analogous to the series 5 runs wherein the LaaRs limit was identified at 55% of 2800 MW RRS with the LaaRs spread uniformly throughout the entire ERCOT system and with all of the LaaRs tripping at the same frequency. The corresponding maximum trip frequency was 59.74 Hz. The series 41 runs indicate the LaaRs limit is 60% of 2300 MW RRS with a 59.72 Hz maximum trip frequency.

**Series 42**

The series 42 runs are analogous to the series 15 runs wherein the LaaRs limit was identified at 50% of 2800 MW RRS with the LaaRs spread uniformly throughout the West Texas CSC zone and with all of the LaaRs tripping at the same frequency. The corresponding maximum trip frequency was 59.72 Hz. The series 42 runs indicate the LaaRs limit is also 50% of 2300 MW RRS but there is no limit within the 59.7 Hz frequency tier (59.70 Hz – 59.78+ Hz) for tripping the LaaRs.

**Series 43**

The series 43 runs are analogous to the series 16 runs wherein the LaaRs limit was identified at 55% of 2800 MW RRS with the LaaRs spread uniformly throughout the North Texas CSC zone and with all of the LaaRs tripping at the same frequency. The corresponding maximum trip frequency was 59.72 Hz. The series 43 runs indicate the LaaRs limit is also 55% of 2300 MW RRS but there is no limit within the 59.7 Hz frequency tier (59.70 Hz – 59.78+ Hz) for tripping the LaaRs.

**Series 44**

The series 44 runs are analogous to the series 17 runs wherein the LaaRs limit was identified at 50% of 2800 MW RRS with the LaaRs spread uniformly throughout the Houston CSC zone and with all of the LaaRs tripping at the same frequency. The corresponding maximum trip frequency was 59.74+ Hz. The series 44 runs indicate the

LaaRs limit is 55% of 2300 MW RRS and no limit within the 59.7 Hz frequency tier (59.70 Hz – 59.78+ Hz) for tripping the LaaRs.

**Series 45**

The series 45 runs are analogous to the series 18 runs wherein the LaaRs limit was identified at 55% of 2800 MW RRS with the LaaRs spread uniformly throughout the South Texas CSC zone and with all of the LaaRs tripping at the same frequency. The corresponding maximum trip frequency was 59.72 Hz. The series 45 runs indicate the LaaRs limit is 55% of 2300 MW RRS with a 59.74 Hz maximum trip frequency.

## **CONCLUSIONS**

Because system inertia is at the lowest levels during light loading, conditions are most favorable for system frequency overshoot. Consequently, the critical operating scenarios for reliable deployment of LaaRs are during periods of light loading. The most significant variables to consider in determining the maximum amount of LaaRs that can be deployed via underfrequency relaying are the frequency trip settings of the LaaR relays. The worst case scenarios for frequency overshoot occur when all of the LaaRs trip at the same frequency set-point. Intermediately, frequency overshoot can be depressed to varying degrees when the frequency set-points of the LaaR relays are spread out over a range of frequencies. Other variables having a more limited relationship with the maximum amount of LaaRs deployable by underfrequency relaying are the geographical locations of the LaaRs. Tables 10 and 11 summarize the various limits on the amount of LaaRs deployable at the 59.7 Hz tier and the conditions associated with each limit.

**Table 10 – Summary of LaaRs Limits at the 59.7 Hz Tier, 2800 MW RRS**

<b>LOCATION OF LaaRs</b>	<b>RELAY TRIP SETTING (Hz)<sup>†</sup></b>	<b>LaaRs LIMIT (% of 2800 MW)</b>	<b>LIMIT BASIS</b>
Existing locations	Existing trip settings: 9.1% @59.8 Hz 0.9% @59.72 Hz 1.4% between 59.71 and 59.72 Hz 10.7% @59.71 Hz 25.4% between 59.70 and 59.71 Hz 52.5% @59.70 Hz	65	Overshoot greater than or equal to 60.4 Hz.
Existing locations	Modified version of the existing trip settings: 0.9% @59.72 Hz 1.4% between 59.71 and 59.72 Hz 10.7% @59.71 Hz 25.4% between 59.70 and 59.71 Hz 61.6% @59.70 Hz	60	
Existing locations	59.72	55	
Uniformly distributed throughout ERCOT	59.74+	55	
Lumped in NTX CSC zone	59.72	55	
Lumped in STX CSC zone	59.74	50	
Lumped in WTX CSC zone	59.72	50	
Lumped in HOU CSC zone	59.74+	50	

<sup>†</sup>The relay trip setting data in row 1 of this table is representative of the existing LaaRs in ERCOT. The relay trip setting numbers in rows 3 through 8 are maximum LaaR trip frequencies assuming all of the LaaRs specified in the “LaaRs LIMIT” column are tripped at the same frequency.

**Table 11 – Summary of LaaRs Limits at the 59.7 Hz Tier, 2300 MW RRS**

LOCATION OF LaaRs	RELAY TRIP SETTING (Hz) <sup>†</sup>	LaaRs LIMIT (% of 2300 MW)	LIMIT BASIS
Existing locations	Existing trip settings: 9.1% @59.8 Hz 0.9% @59.72 Hz 1.4% between 59.71 and 59.72 Hz 10.7% @59.71 Hz 25.4% between 59.70 and 59.71 Hz 52.5% @59.70 Hz	70	Overshoot greater than or equal to 60.4 Hz.
Existing locations	Modified version of the existing trip settings: 0.9% @59.72 Hz 1.4% between 59.71 and 59.72 Hz 10.7% @59.71 Hz 25.4% between 59.70 and 59.71 Hz 61.6% @59.70 Hz	65	
Existing locations	59.74	60	
Uniformly distributed throughout ERCOT	59.72	60	
Lumped in NTX CSC zone	59.78+	55	
Lumped in STX CSC zone	59.74	55	
Lumped in WTX CSC zone	59.78+	50	
Lumped in HOU CSC zone	59.78+	55	

<sup>†</sup>The relay trip setting data in row 1 of this table is representative of the existing LaaRs in ERCOT. The relay trip setting numbers in rows 3 through 8 are maximum LaaR trip frequencies assuming all of the LaaRs specified in the “LaaRs LIMIT” column are tripped at the same frequency.

Results from simulations of LaaRs deployed at the 59.8 Hz tier indicate such LaaRs cannot be reliably deployed with the 59.7 Hz tier LaaRs operated at the critical levels identified in tables 10 and 11. The maximum amount of LaaRs and corresponding maximum relay trip settings that can be reliably deployed at the 59.8 Hz tier is a function of where limits are established for the amount of LaaRs and corresponding relay trip settings at the 59.7 Hz tier. Therefore, the DWG will need guidance from ROS on where the 59.7 Hz tier limits will be set in order to define LaaR limits for the 59.8 Hz tier.

Section 6.10.3.2 of the ERCOT Protocols allow a LaaR to be deployed at up to 150% of the amount requested by ERCOT at the time of testing the LaaR. This potential variance between contracted and actual LaaR amount should be considered when establishing LaaR limits.