The Need for Faster Underfrequency Load Shedding

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74th Annual Texas A&M Conference for Protective Relay Engineers
March 24, 2021

Presentation Outline

- What is Automatic Underfrequency Load Shedding (UFLS)?
- What is the Purpose of UFLS?
- Brief History of UFLS
- UFLS Technical Basics
- Xcel Energy New Mexico/Texas Need for UFLS
- UFLS Regional/Local Practices
- Modern Day UFLS Challenges
- Modern Day UFLS Solution
- Conclusions

What is Automatic UFLS?

- **Automatic UFLS is a last-ditch, first line of defense to prevent blackouts and generator steam turbine damage**
- **Underfrequency relays are scattered throughout power system, usually at distribution substations**
- **Relays monitor voltage frequency based off zero crossings**
- **Relay elements will assert when monitored frequency reaches an underfrequency setpoint**
- **Relay will issue a trip after a timer expires (typically 6–30 cycles)**
- **UFLS programs require tripping for underfrequency conditions below 59.5 Hz**
- **UFLS programs typically have three or more underfrequency levels, each designed to trip a percentage of total system load**

What is the purpose of UFLS?

- **Blackout avoidance**
- **Preventative generator turbine damage**

Steam Turbine
Frequency-Time Damage Table

Frequency at Full Load (Hz)	Minimum Time to Damage (Min.)
59.4	-----
58.8	90
58.2	10
57.6	1

Time is CUMULATIVE over the life of the machine!!

	PRC-024-2 Allowable Low Frequency Tripping Time Delay (Sec.)		
Frequency (Hz)	Eastern Interconnection *	Western Interconnection	ERCOT Interconnection
> 59.5 Hz	Continuous	Continuous	Continuous
≤ 59.5 Hz	1792	Continuous	Continuous
> 59.4 Hz	1201	Continuous	Continuous
≤ 59.4 Hz	1201	180	540
≤ 59.0 Hz	242	180	540
≤ 58.4 Hz	22	30	30
≤ 58.0 Hz	4.44	30	2
≤ 57.8 Hz	0	7.5	2
≤ 57.5 Hz	0	7.5	0
≤ 57.3 Hz	0	0.75	0
≤ 57.0 Hz	0	0	0

* EI tripping times follow the formula $10^{(1.7373*f - 100.116)}$ for frequency values > 57.8 Hz and ≤ 59.5 Hz. This formula was applied to fill in EI values in table at frequency shown.

Brief History of UFLS

- 1965 Northeast Blackout
- 2003 Northeast Blackout
- 2011 Arizona-Southern California Blackout
- 2016 South Australia Blackout

Blackout	Load Lost (MW)	People Affected (Millions)	Interesting Facts
1965 NE	20,000	30	Min. UFLS; NERC[1] formed 3 years later
2003 NE	62,000	50	26,000 MW UFLS; NERC[2] Standards
2011 Arizona-SoCo	7,835	2.7	ALL UFLS tripped; –3 Hz/s ROCOF
2016 S. Australia	1,826	0.85	ALL UFLS tripped; –6 Hz/s ROCOF

[1] National Electric Reliability Council
[2] North American Electric Reliability Corporation

UFLS Technical Basics

- What causes underfrequency events?
  - Loss of generation (Load Served > Generation)
  - Separation events causing loss of import power
- How does the system respond to an underfrequency event?
  - Generators and motor loads slow down as frequency decays
  - System inertia (H) arrests the decay of frequency until governor response activates
  - Generator governors activate about 3 seconds after a frequency excursion to increase electrical power output (MW) into the system to assist in frequency recovery to nominal frequency
- If frequency decays far enough, underfrequency relays trip to shed load to offset lost generation/import power
- In the worst case, frequency decays far enough to cause generation to trip, leading to a blackout!

UFLS Technical Basics

- **Frequency rise/decay can be simulated using equations from [2]:**

$$f = f_{sys} - \Delta L \cdot (1 - e^{-\frac{t}{T}}) \cdot K \cdot 60$$

Time (s)

System Frequency (60 Hz)

$$T = \frac{M}{D} \qquad K = \frac{1}{D}$$

Change in Load (–) or Generation (+) in pu

System Inertia in $\mathrm{MW} \cdot s / MVA$

$$M = 2 \cdot H$$

Final Frequency

$$f = f_{sys} - \Delta L \cdot (1 - e^{-\frac{D \cdot t}{2 \cdot H}}) \cdot \frac{1}{D} \cdot 60$$

Load Damping Constant in pu

$$D = \frac{Load_{Sys} \cdot 1.5}{100}$$

REFERENCES:

[1] P. Kundur, "Load Response to Frequency Deviation," in *Power System Stability and Control*, McGraw-Hill, Inc., 1994, pp. 584 – 587.

[2] P. Kundur, "Factors Influencing Frequency Decay," in *Power System Stability and Control*, McGraw-Hill, Inc., 1994, p. 625.

[3] P. Kundur, "Composite Regulating Characteristic of Power Systems," in *Power System Stability and Control*, McGraw-Hill, Inc., 1994, pp. 595 – 597.

UFLS Technical Basics

- **Rate of Change of Frequency (ROCOF):**

$$f = f_{sys} - \Delta L \cdot (1 - e^{-\frac{D \cdot t}{2 \cdot H}}) \cdot \frac{1}{D} \cdot 60$$

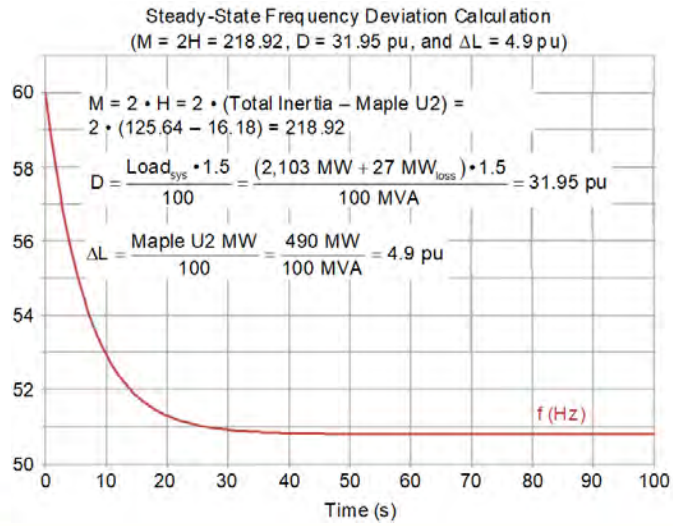
$$\frac{df}{dt} = \frac{-30 \cdot \Delta L}{H} \cdot e^{-\frac{D \cdot t}{2 \cdot H}}$$

Solve at t = 0

$$\frac{df}{dt} = \frac{-30 \cdot \Delta L}{H}$$

UFLS Technical Basics

- **Example using UFLS Test System data:**



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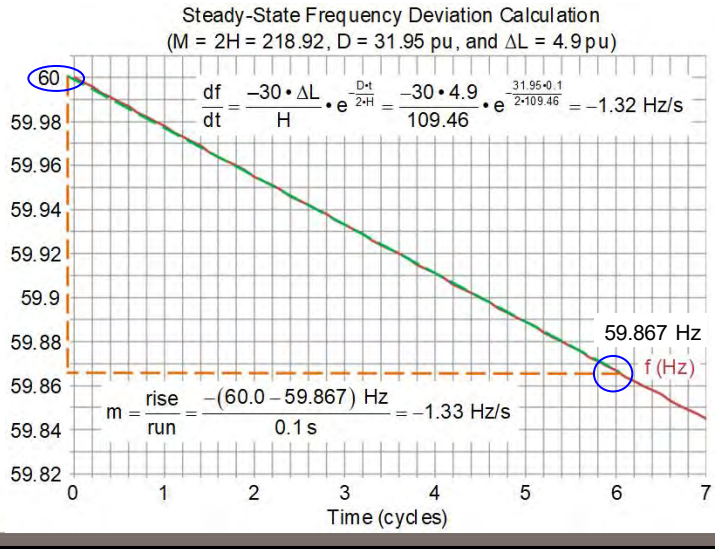
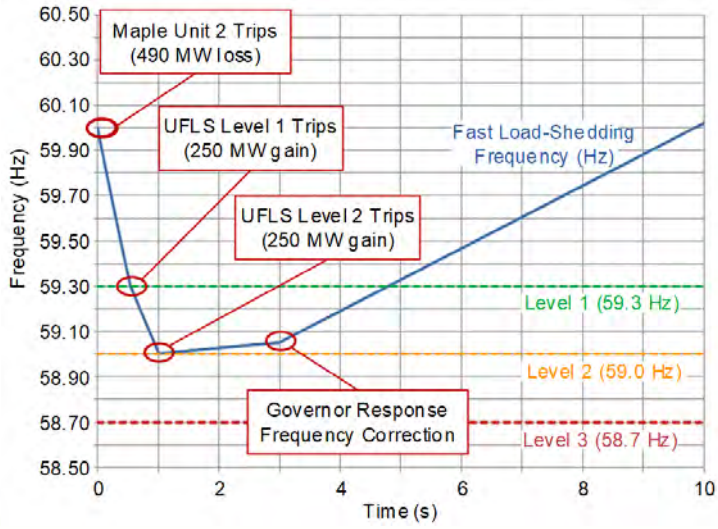


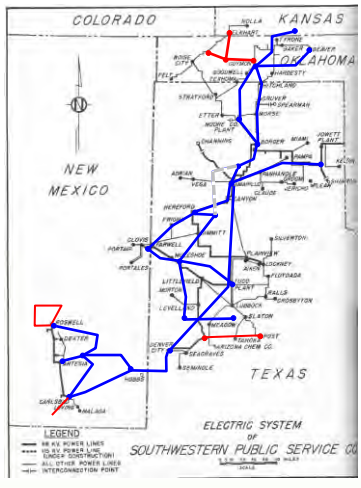
UFLS Technical Basics

- **UFLS "Hand Calculations" using Test System data:**



Xcel Energy NM/TX Need for UFLS

- **Prior to 1964, Xcel Energy NM/TX did not utilize UFLS**
- **In 1964, a major blackout changed that practice!**



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- Prior to 1964, Xcel Energy NM/TX did not utilize UFLS
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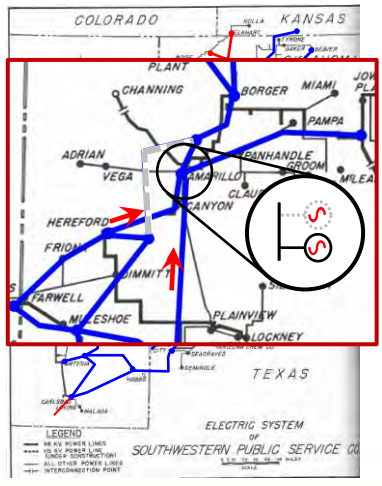
- A large Amarillo generating unit was offline for maintenance
- A major 115 kV line was also out-of-service for maintenance
- Heavier than normal S-N flows into the Amarillo area were occurring due to the unit outage
- A second unit at the same station tripped on loss of excitation, causing power swings across the tie lines



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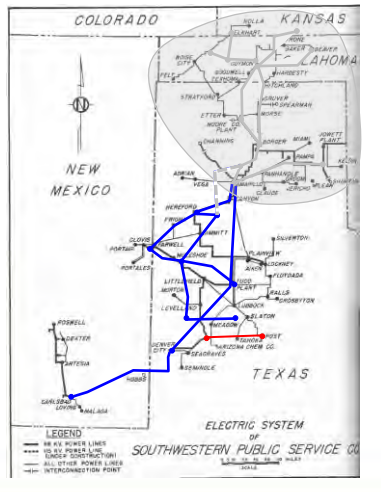
- The north—south tie lines tripped, resulting in a Texas North blackout



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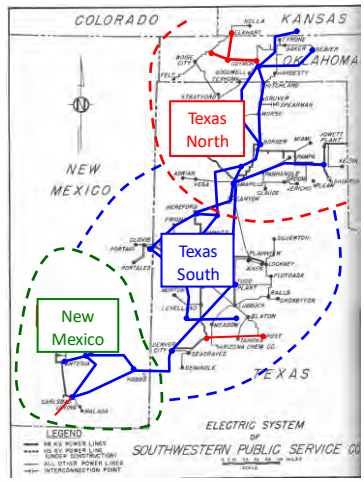
Xcel Energy NM/TX Need for UFLS

1964 Lessons Learned

- Out-of-step tripping was allowed to force islanding at strategic locations to create three load/generation islands
- PSB was installed on all looped transmission lines
- Underfrequency relaying was installed throughout the system at three steps
- About 10% of system load was to be shed at each UF step



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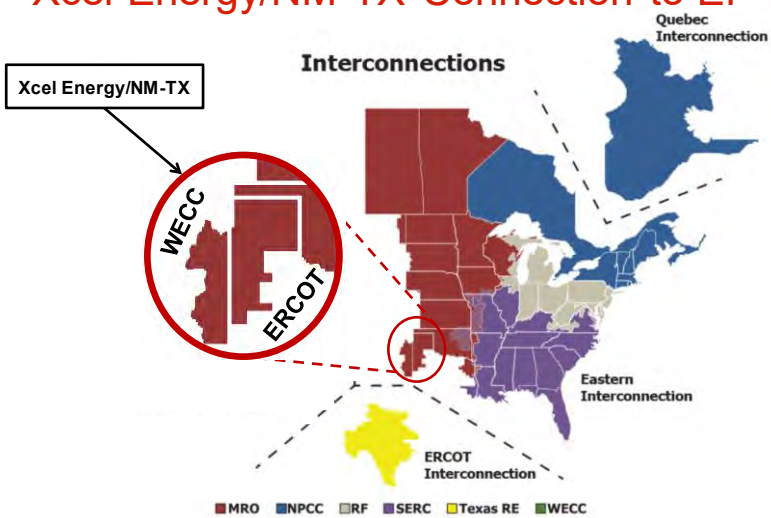
Xcel Energy/NM-TX Connection to EI



NERC Map Source: https://www.nerc.com/AboutNERC/keyplayers/PublishingImages/NERC_Interconnections_01JUL19.jpg

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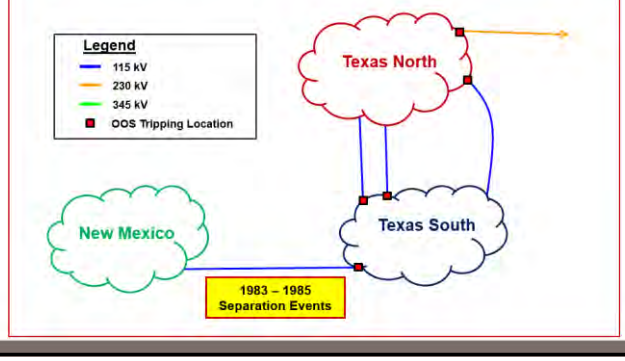
Xcel Energy NM/TX UFLS "Tests"

Separation Event Date(s)	Tie Lines OUT	Tie Lines TRIPPED	Lowest UFLS Step Tripped	UFLS Load Tripped	TOTAL Load Tripped
1983–1985	0	1	59.3 Hz	<350 MW	<350 MW

Eleven EI trips with UFLS in two year span!!



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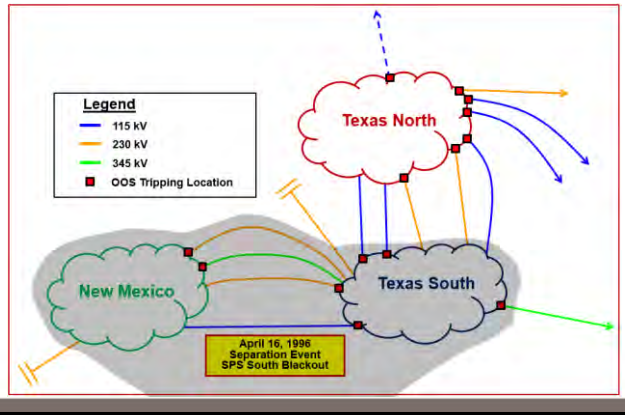

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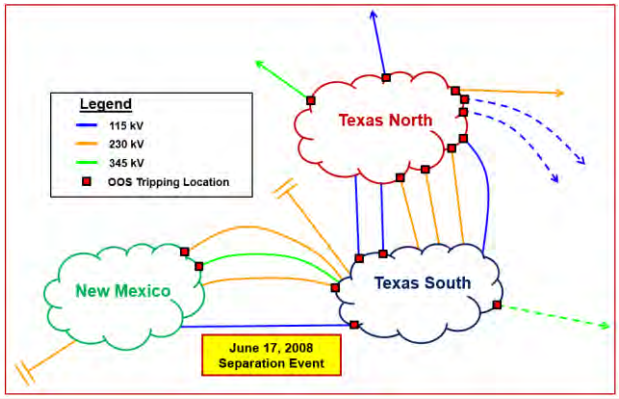
April 16, 1996	1	4	58.7 Hz	750 MW	2000 MW
June 17, 2008	3	3	59.3 Hz	650 MW	650 MW



UFLS Regional/Local Practices

- **The planning coordinator for the Xcel Energy NM/TX region is the Southwest Power Pool (SPP)**
- **Per NERC standard PRC-006, SPP developed a UFLS program summarized below**

UFLS Step	Frequency (Hz)	Minimum Accumulated Load Relief as Percentage of Forecasted Peak Load (%)	Maximum Accumulated Load Relief as Percentage of Forecasted Peak Load (%)
1	**59.3**	10	25
2	**59.0**	20	35
3	**58.7**	30	45

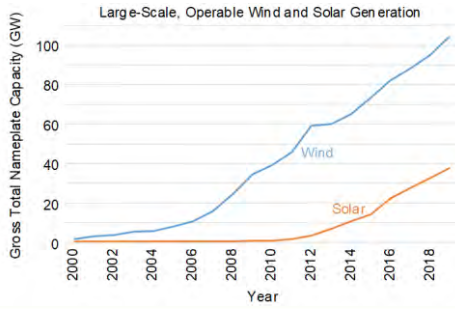
- Intentional time delay less than or equal to 30 cycles
- Undervoltage inhibit less than or equal to 85% nominal voltage

- **Xcel Energy NM/TX uses normal intentional time delays of 6 cycles and 30 cycles where feeders have significant motor load**
- **Xcel Energy NM/TX uses an undervoltage inhibit setting of 67%**

Modern Day UFLS Challenges

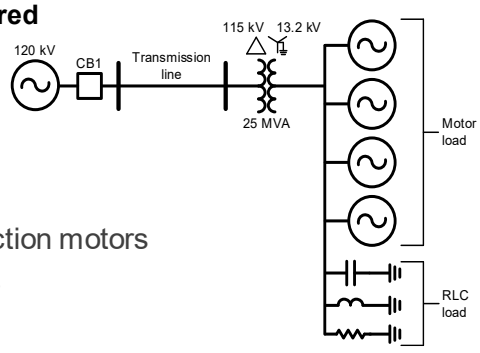
- **Significant amounts of UFLS with extended time delays**
- **Higher ROCOF caused by increasing penetrations of renewable resources**

UFLS Level	Frequency (Hz)	Percentage of Underfrequency Relays with Intentional Time Delay = 6-cycles	Percentage of Underfrequency Relays with Intentional Time Delay = 30-cycles
1	59.3	57%	43%
2	59.0	70%	30%
3	58.7	62%	38%
OVERALL		64%	36%



Modern Day UFLS Challenges

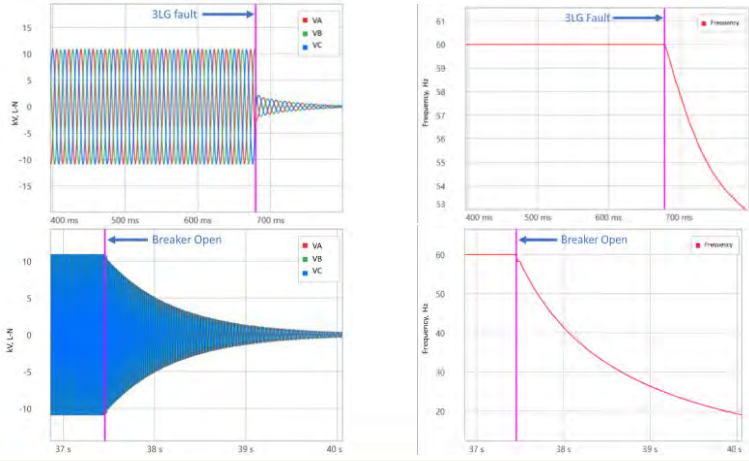
- **Electromagnetic Transient Software (EMTS) program model is used to test for UFLS relay mis-trip under transient or lost source conditions**
- **Two commercially available EMTS programs were used and results were compared**



- Four induction motors
- RLC loads

Modern Day UFLS Challenges

- **Transient conditions can cause voltage and frequency to decrease**
  - **Fault on the transmission line or step-down transformer**
  - **Motor spin-down after the source transmission breaker opens**



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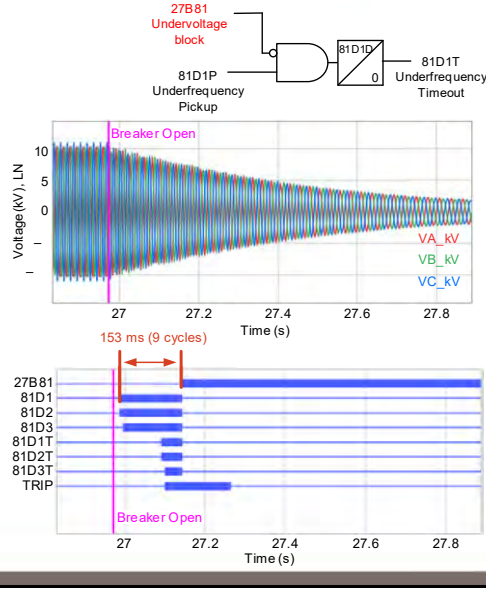
Modern Day UFLS Challenges

- Standard UFLS relay has undervoltage inhibit
- 6-cycle intentional UFLS delay is not sufficient on feeders with significant motor load
- It takes 9 cycles for voltage to decay below the undervoltage block setting
- All three levels of underfrequency time out and trip
- 30-cycle intentional time delay would be secure from misoperation

Voltage supervision



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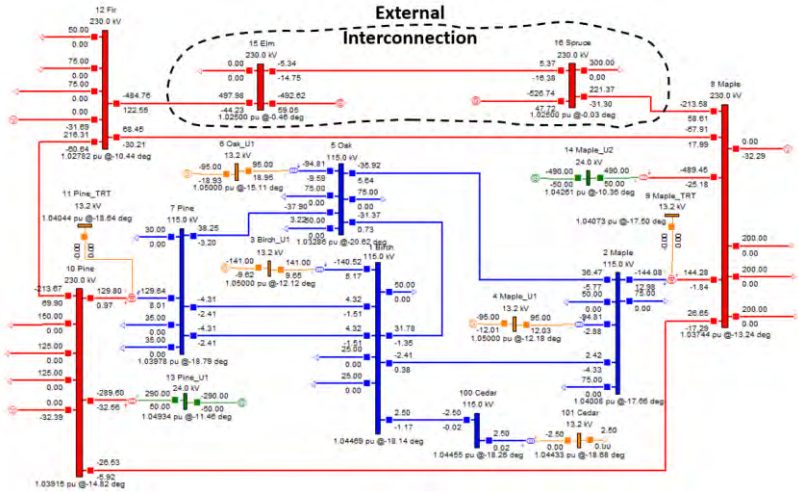
Modern Day UFLS Challenges

- **Comparison of Time Delays – 6 cycles vs. 30 cycles:**

Test#	RLC load connected	# of Motors connected	UFLS Levels 1, 2, 3 6 cycle delay	UFLS Levels 1, 2, 3 30 cycle delay
1	Resistor	4	Trip	No Op
2	Resistor	3	Trip	No Op
3	Resistor	2	Trip	No Op
4	Resistor	1	Trip	No Op
5	Capacitor	4	Trip	No Op
6	Capacitor	3	Trip	No Op
7	Capacitor	2	Trip	No Op
8	Capacitor	1	Trip	Trip
9	Inductor	4	Trip	No Op
10	Inductor	3	Trip	No Op
11	Inductor	2	Trip	No Op
12	Inductor	1	Trip	No Op
13	None	4	Trip	No Op
14	None	3	Trip	No Op
15	None	2	Trip	No Op
16	None	1	Trip	No Op

Modern Day UFLS Challenges

- **How do we study and assess the impact of these challenges?**
- **With a reduced, representative test system model:**

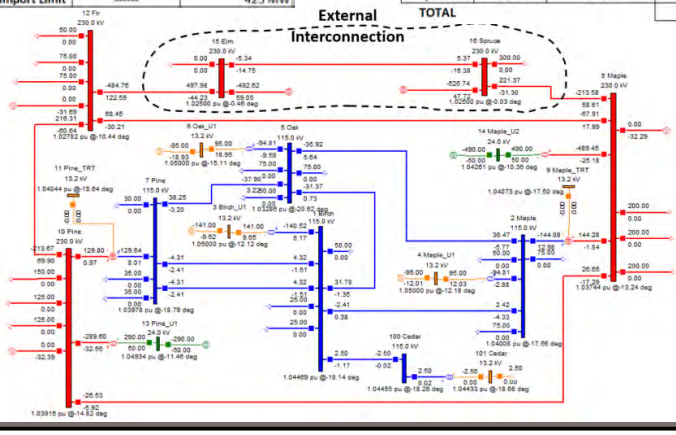


Modern Day UFLS Challenges

- **Test system details:**

	Case Study Actual	System Peak/Limit
Internal System Load	1803 MW	2000 MW
Internal System Generation	1111 MW	1150 MW
External System Load	300 MW	------
External System Generation	1019 MW	2000 MW
Internal System Import	698 MW	1200 MW
Fir - Elm Import Limit	------	900 MW
Maple - Spruce Import Limit	------	425 MW

Generator Name	Nameplate MVA	Generator Inertia Constant (H)	Generator Inertia @ 100 MVA Base
Birch U1	150	6.22	9.33
Oak U1	100	5.48	5.48
Pine U1	300	3.33	9.99
Maple U1	100	5.48	5.48
Maple U2	500	3.236	16.18
Elm	1000	3.959	39.59
Spruce	1000	3.959	39.59
TOTAL			125.64



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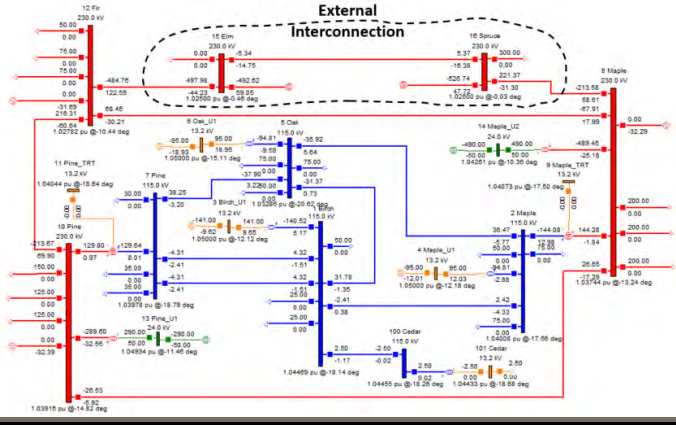
Modern Day UFLS Challenges

- **Test system details:**

UFLS Step	Freq. (Hz)	Percent of Peak Load Shed (%)	Load Shed with 6-Cycle Delay (MW)	Load Shed with 30-Cycle Delay (MW)	Total Load Shed (MW)
1	59.3	12.5	150	100	250
2	59.0	12.5	150	100	250
3	58.7	12.5	150	100	250

Case	Total Synchronous Generation (MVA)	Total Wind Generation (MVA)	% Wind Penetration
1	3150	0	0%
2	2350	800	25%
3	1550	1600	50%
4	1050	2100	67%



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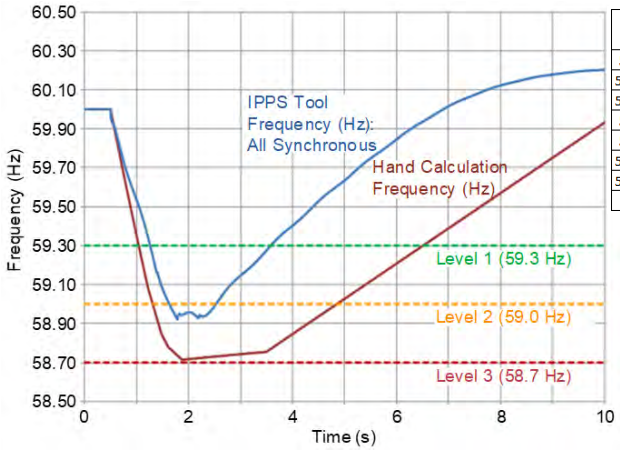
Modern Day UFLS Challenges

- **All Synchronous Generation Test:**



Step	Load (MW)	Shunt	Substation	Time (Sec.)	f (Hz)
59.3_6_CYC	150	10-1	Pine	1.388	59.159
59.3_30_CYC	75	5-1	Oak	1.788	58.921
59.3_30_CYC	25	1-2	Birch	1.788	58.921
59.0_6_CYC	75	12-1	Fir	1.808	58.940
59.0_6_CYC	75	12-2	Fir	1.808	58.940
59.0_30_CYC	50	5-3	Oak	2.192	58.927
59.0_30_CYC	50	2-3	Maple	2.200	58.934
Total	500	MW			

ROCOF	-0.95 Hz/s
Nadir	58.92 Hz
Time to Nadir	1.79 sec.
Final Frequency	60.20 Hz

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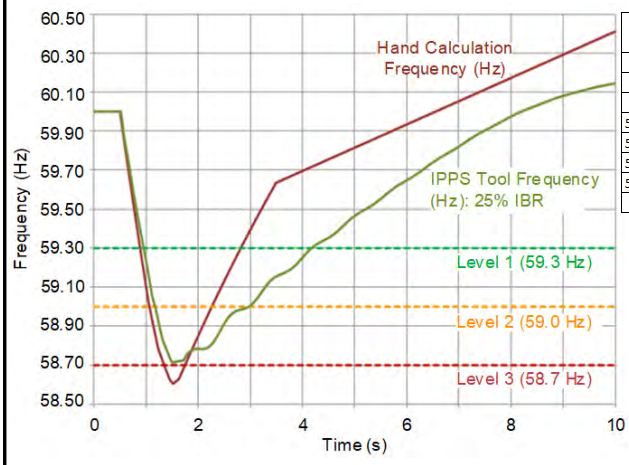
How do we Evaluate these Challenges??

Modern Day UFLS Challenges

- **25% Wind Generation Test:**



Step	Load (MW)	Shunt	Substation	Time (Sec.)	f (Hz)
59.3_6_CYC	150	10-1	Pine	1.100	59.082
59.0_6_CYC	75	12-1	Fir	1.304	58.844
59.0_6_CYC	75	12-2	Fir	1.304	58.844
59.3_30_CYC	75	5-1	Oak	1.500	58.713
59.3_30_CYC	25	1-2	Birch	1.500	58.713
59.0_30_CYC	50	2-3	Maple	1.708	58.723
59.0_30_CYC	50	5-3	Oak	1.717	58.724
Total	500	MW			

ROCOF	-1.53 Hz/s
Nadir	58.71 Hz
Time to Nadir	1.50 sec.
Final Frequency	60.10 Hz

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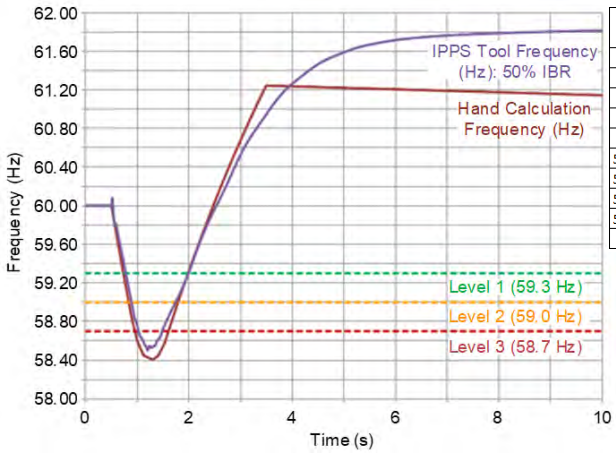
Modern Day UFLS Challenges

- **50% Wind Generation Test:**



Step	Load (MW)	Shunt	Substation	Time (Sec.)	f (Hz)
59.3_6_CYC	150	10-1	Pine	0.929	58.892
59.0_6_CYC	75	12-1	Fir	1.038	58.678
59.0_6_CYC	75	12-2	Fir	1.038	58.678
58.7_6_CYC	75	2-1	Maple	1.179	58.532
58.7_6_CYC	75	2-2	Maple	1.179	58.532
59.3_30_CYC	75	5-1	Oak	1.329	58.543
59.3_30_CYC	25	1-2	Birch	1.329	58.543
59.0_30_CYC	50	5-3	Oak	1.442	58.636
59.0_30_CYC	50	2-3	Maple	1.442	58.636
Total	650	MW			

ROCOF	-2.58 Hz/s
Nadir	58.50 Hz
Time to Nadir	1.20 sec.
Final Frequency	61.80 Hz

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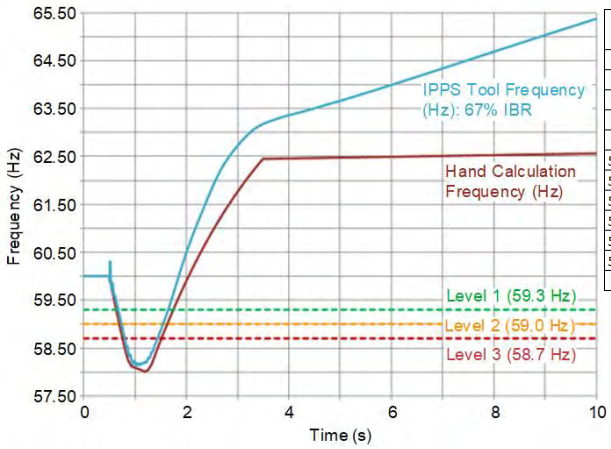
Modern Day UFLS Challenges

- **67% Wind Generation Test:**



Step	Load (MW)	Shunt	Substation	Time (Sec.)	f (Hz)
59.3_6_CYC	150	10-1	Pine	0.813	58.641
59.0_6_CYC	75	12-1	Fir	0.875	58.393
59.0_6_CYC	75	12-2	Fir	0.875	58.393
58.7_6_CYC	75	2-1	Maple	0.946	58.215
58.7_6_CYC	75	2-2	Maple	0.946	58.215
59.3_30_CYC	75	5-1	Oak	1.213	58.205
59.3_30_CYC	25	1-2	Birch	1.213	58.205
59.0_30_CYC	50	2-3	Maple	1.279	58.285
59.0_30_CYC	50	5-3	Oak	1.279	58.285
58.7_30_CYC	75	5-2	Oak	1.350	58.429
58.7_30_CYC	25	1-3	Birch	1.354	58.445
Total	750	MW			

ROCOF	-4.34 Hz/s
Nadir	58.14 Hz
Time to Nadir	1.07 sec.
Final Frequency	65.50 Hz

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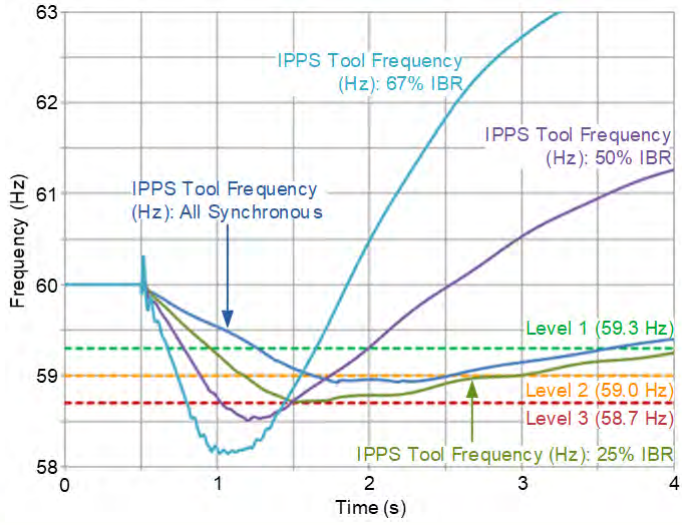
Modern Day UFLS Challenges

- **ALL Test Cases:**



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Modern Day UFLS Solution

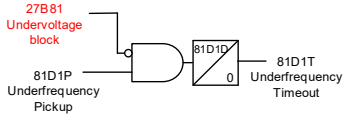
- **Use Supervision of Underfrequency Elements from IEEE C37.117**

C37.117-2007 - IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration

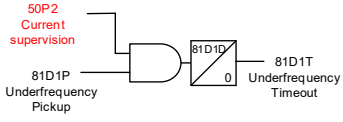
Publisher: IEEE Cite This PDF

Status: Inactive - Reserved

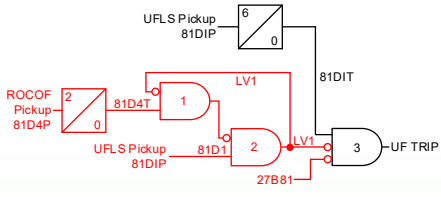
Voltage supervision



Current supervision



ROCOF supervision



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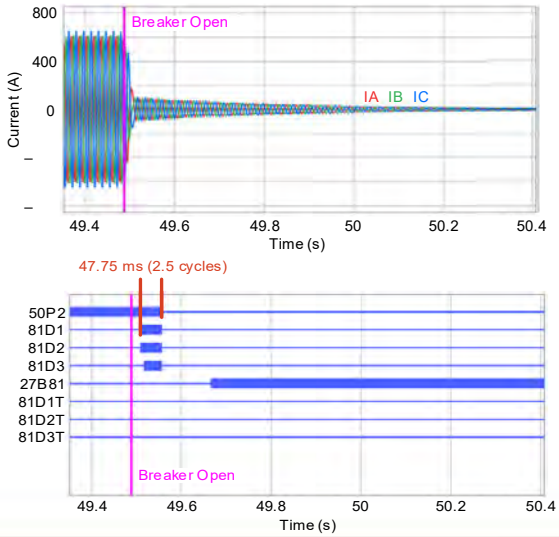
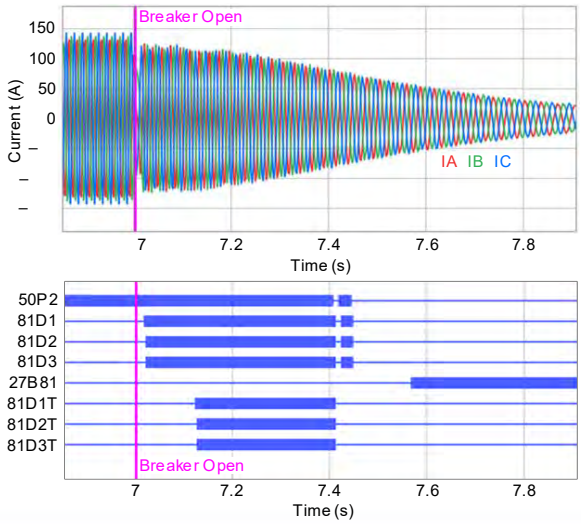
Modern Day UFLS Solution

- **Current Supervision:**
  - Current supervision (50P2) pickup is set to 50% of one motor at full load
  - 50P2 drops out 2.5 cycles after 81 picks up
  - Current supervision correctly blocks all three levels of 81 from timing out



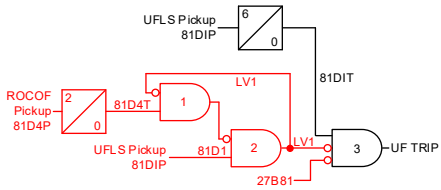
Modern Day UFLS Solution

- **Current Supervision:**
  - Successful current supervision depends on how quickly current decays
  - In this case, the current takes much longer than 6 cycles and cannot provide adequate supervision



Modern Day UFLS Solution

- **ROCOF Supervision:**



$$\text{ROCOF supervision} = \frac{81D4P - 81DIP}{81D4D / 60} = \frac{59.7 - 59.3\ \text{Hz}}{2 / 60\ \text{s}} = 12\ \text{Hz/s}$$

- The worst-case (lowest) ROCOF for motor bus de-energization was 34 Hz/s
- Frequency decay experienced in South Australia during the 2016 blackout was 6 Hz/s

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Modern Day UFLS Solution

- **Summary of Supervision Methods:**

Test	RLC Load Connection	Number of Motors Connected	UFLS With Undervoltage Block = 67%	UFLS With Undervoltage Block = 80%	UFLS With Current Supervision	UFLS With ROCOF Supervision
1	Resistor	4	Trip	No Op	No Op	No Op
2	Resistor	3	Trip	No Op	No Op	No Op
3	Resistor	2	Trip	No Op	No Op	No Op
4	Resistor	1	Trip	No Op	No Op	No Op
5	Capacitor	4	Trip	No Op	No Op	No Op
6	Capacitor	3	Trip	Trip	No Op	No Op
7	Capacitor	2	Trip	Trip	Trip	No Op
8	Capacitor	1	Trip	Trip	Trip	No Op
9	Inductor	4	Trip	No Op	No Op	No Op
10	Inductor	3	Trip	No Op	No Op	No Op
11	Inductor	2	Trip	No Op	No Op	No Op
12	Inductor	1	Trip	No Op	No Op	No Op
13	None	4	Trip	No Op	No Op	No Op
14	None	3	Trip	No Op	No Op	No Op
15	None	2	Trip	Trip	No Op	No Op
16	None	1	Trip	Trip	Trip	No Op

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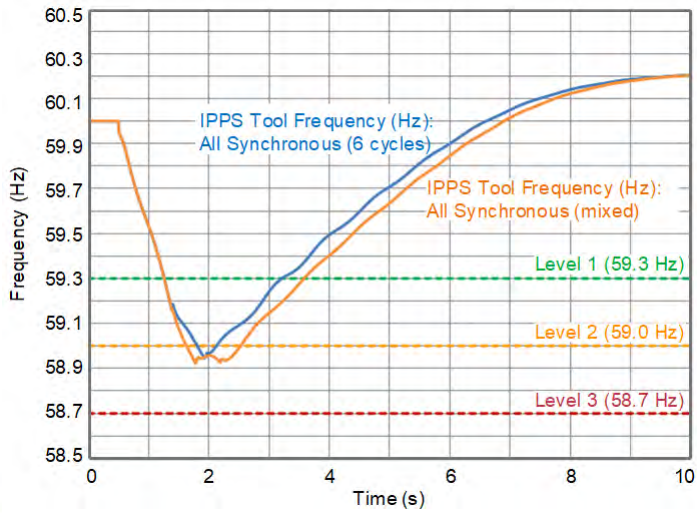
Modern Day UFLS Solution Test

- Implementing ROCOF supervision in addition to undervoltage supervision allows secure implementation of lower UFLS intentional time delays
- ALL time delays can be lowered to 6 cycles
- UFLS Test System studies can be performed with these lower time delays to evaluate the solution's effectiveness

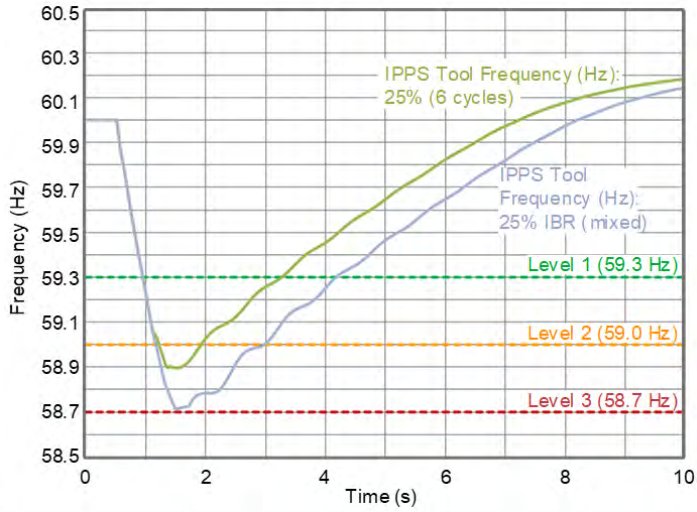
Modern Day UFLS Solution Test

- All Synchronous Generation Test:



Modern Day UFLS Solution Test

- **25% Wind Generation Test:**



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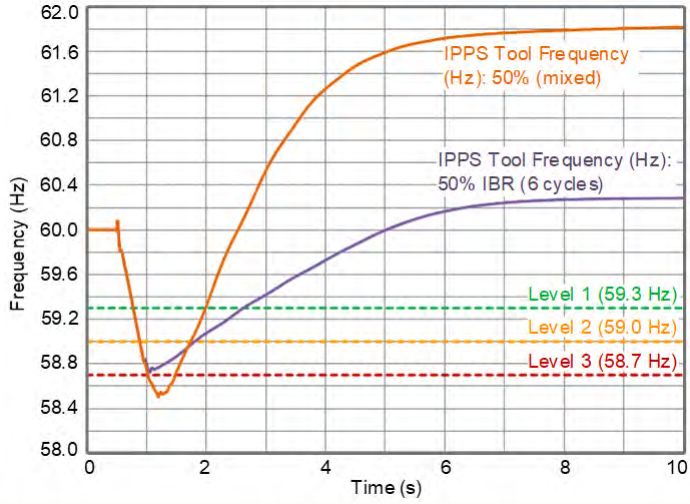
Modern Day UFLS Solution Test

- **50% Wind Generation Test:**



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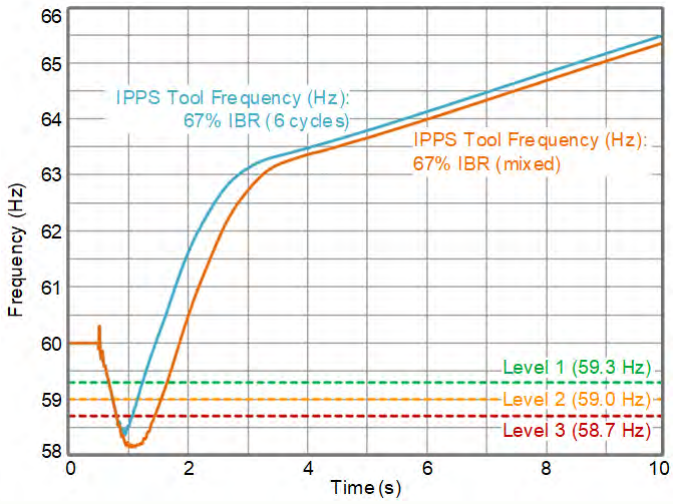
Modern Day UFLS Solution Test

- **67% Wind Generation Test:**



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Conclusions

- **Verified that the 6-cycle UFLS time delay is too short to avoid UFLS relay mis-trips when source transmission line outages feeders with significant motor load**
- **Verified that the 30-cycle UFLS time delay prevents most UFLS misoperations due to motor spin-down**
- **Proved that increased penetrations of renewable resources result in faster ROCOF, lower frequency nadir, and more load shed for UFLS events**
- **Proved that the ROCOF supervisory scheme is the most secure of the three supervisory methods tested in preventing UFLS misoperations due to motor spin-down**
- **Verified that implementation of ROCOF supervision of UFLS relays allowing use of 6-cycle time delays results in lower frequency nadir, faster recovery to nominal frequency, and less load shed**

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Future Considerations/Developments

- Studies need to be performed to see if UFLS time delays can be further reduced to 3–4 cycles
- Studies need to be performed to see if shedding more load in Level 1 or additional load shed steps improves UFLS program performance
- Addition of transmission elements should be studied to determine an affordable mix to enhance UFLS program performance
  - Addition of synchronous condensers to replace lost system inertia
  - Addition of battery energy storage systems (BESSs) to provide fast frequency response for under/overfrequency conditions

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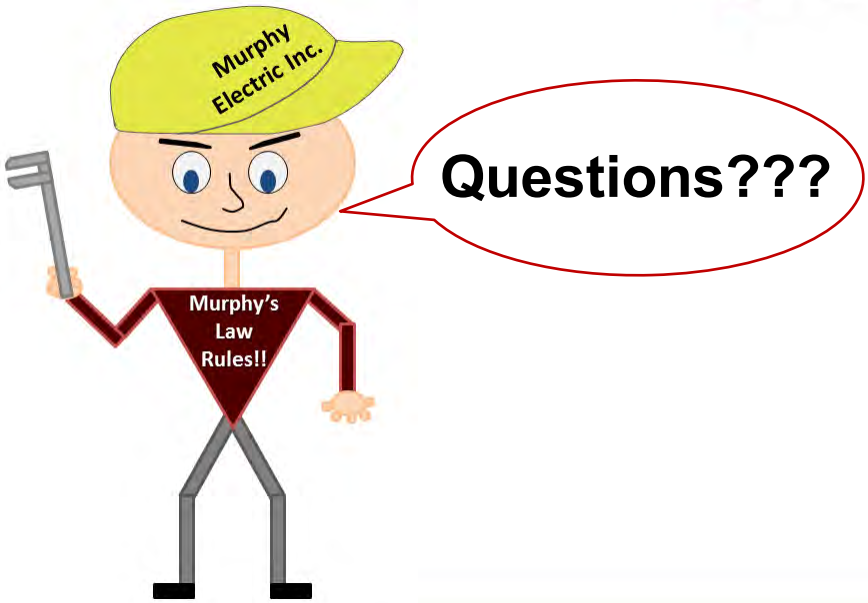

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