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Measurement and Simulation of Wide-area Frequency in US Eastern Interconnected Power System

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Abstract – An internet-based, real-time GPS synchronized wide-area power system frequency monitoring network(FNET) has been monitoring wide-area power system frequency in continuous time in the United States. This paper analyzes the FNET measurement to the verified disturbances in the US eastern interconnected power system and simulates it using the dynamic system model. By comparing the frequency measurements with its simulation results to the same disturbances in detail, this paper finds that the sequence of monitoring points to detect the frequency fluctuation caused by the disturbances is matched well in the measured data and the simulation results. The similarity comparison index is also proposed to quantify the similarity of the compared cases. The dynamic model based simulation result is expected to compensate for the lack of FNET measurement in its applications.

Keywords: Wide-area power system frequency, Internet based real-time GPS synchronized wide area Frequency Monitoring Network(FNET), System disturbance, Frequency Disturbance Recorder(FDR), Power system simulation, Detection sequence.

1. Introduction

An internet-based real-time GPS synchronized wide area Frequency Monitoring Network(FNET) has been monitoring the power system frequency in continuous time at more than 40 locations in the United States, and accumulated the measurement in its database [1-3]. Since frequency is one of the most informative parameters indicating the power balance in the power system, the actual frequency responses to a system disturbance can help us understand the global characteristics of the bulk power systems more correctly and develop the analysis tool of the power systems status. The frequency measurement in the FNET database shows that the frequency excursion due to the sudden drop of a generator propagates along the electrical connections from the event location to the rest of power systems [4, 5]. One of the FNET applications uses the time delay of the measured frequency excursion at different monitoring locations to locate the dropped generator, and this will help power system operators in ascertaining the cause of the sudden frequency excursion especially when it occurs not in their control area but in the neighboring systems [6, 7]. Such FNET application studies would usually require large number of frequency measurements to the system disturbances which should be confirmed by power utilities, but the actually occurred disturbances arerareand not every frequency excursion measured by FNET could be verified. Therefore, the dynamic model based simulation is expected to compensate for the lack of such frequency measurements to various system disturbances in FNET applications. However, it has been pointed out that the simulation can not exactly represent the actual systems since the power system model cannot exactly represent the various conditions of actual power systems00. Actually, there has not been even specific comparison between the measurement and simulation results for the same event.

For this, this paper simulates the frequency responses to the same disturbances measured by FNET using the latest model of the US Eastern power system, and compares simulations results with the measurement data to see how those are different and if there is any possibility of using the simulation results for FNET applications. The similarity between frequency measurements and its recreating simulation would be used to compensate for the lack of the FNET measurement to the disturbances.

2. Frequency Measurement

The FNET collects the power system frequency measured and GPS-synchronized by a local frequency disturbance recorder(FDR) through the internet, allowing us to monitor the wide-area power system frequency with low cost and high accuracy [1, 2].

Based on the measured data, the FNET has developed a database of the wide-area frequency in U.S. power systems. From the database which has kept all data collected from each FDR for several years, eight events of generator trips

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could be confirmed by power utilities. Table 1 summarizes these disturbances with their detailed locations.

The various resources from the U.S. Nuclear Regulatory Commission(U.S.NRC), Genscape Inc., and Energy Information Administration(EIA) were used to confirm these events measured by FNET000. Table 2 shows FDR units which measured the frequency at those locations when these events occurred.

When the power system frequency suddenly drops due to a tripped generator, time differences in detecting such frequency drops among different measuring points have been monitored and this can be understood as the propagation of the power system frequency excursion from the location of the tripped generator.

Table 1. Confirmed generator trips in FNET database

	Tripped Generator	Location
Event 1	Davis Besse	Ottawa, OH
Event 2	Watts Bar	Rhea, TN
Event 3	Browns Ferry	Limestone, AL
Event 4	East Bend	Boone, KY
Event 5	Browns Ferry	Limestone, AL
Event 6	Cumberland	Stewart, TN
Event 7	W H Zimmer	Clermont, OH
Event 8	Wilson	Burke, GA

Table 2. Locations of FDR units

FDR ID	FDR NAME	CITY	Latitude	Longitude
1	NY	Schenectady, NY	42.8018	-73.9281
2	UMR	Rolla, MO	37.9487	-91.7658
3	ARI	Alexandria, VA	38.8210	-77.0862
4	VT	Blacksburg, VA	37.2327	-80.4284
6	ABB	Raleigh, NC	35.8220	-78.6587
7	MISS	Mississippi State, MS	33.4567	-88.8222
9	UFL	Gainesville, FL	29.6742	-82.3363
11	Calvin	Grand Rapids, MI	42.9613	-85.6557
17	Tulane	New Orleans, LA	30.0658	-89.9313
20	TVA1	Chattanooga, TN	35.1313	-84.8750

Table 3. Detection sequences and distances of FDRS from the event location in the measurement

Event		Freq. Drop Detection Sequence of monitoring pts. and their distances from the tripped Gen								
#1	FDR #	4	6	3	2	7	9			
	Distance[mi]	328	458	365	510	631	820			
#2	FDR #	7	2	6	4	3	11			
	Distance[mi]	272	419	346	269	485	438			
#3	FDR #	7	2	6	4	3	11			
	Distance[mi]	134	369	474	411	630	589			
#4	FDR #	3	6	11	2	4	7			
	Distance[mi]	405	384	287	389	253	437			
#5	FDR #	7	2	9	6	4	11	3		
	Distance[mi]	134	369	420	474	411	589	630		
#6	FDR #	20	7	2	9	6	11	4	3	
	Distance[mi]	176	212	254	549	501	468	405	611	
#7	FDR #	4	11	3	20	6	2	7	9	
	Distance[mi]	238	283	383	271	371	412	457	654	
#8	FDR #	9	7	20	6	4	17	3	2	11
	Distance[mi]	236	396	219	270	301	504	488	658	504

In Table 3, FDR units are aligned by the sequence of detecting the frequency drops. Table 3 also shows the distances of FDR units from event locations.

Since the frequency response of the power system to the generator trip propagates along the power grid, the time at which a FDR unit detects the frequency distortion depends on its electrical distance from the tripped generator. The electrical distance is a concept used to explain generators' synchronizing power coefficient as the machine electrically close to the point of the power impact will pick up the greater share of the load regardless of their size0. Therefore, in some cases as shown in Table 3, geographically further FDR units from the event location measured the frequency distortion earlier than the closer FDR units in several cases. In particular, in a region such as the center of the U.S. where the power grid is relatively sparse, this phenomenon appears dominant. For example, in the case of event2, the frequency drop due to the generator trip at Watts Bar in Tennessee was not measured first by an FDR unit(#4) in Blacksburg, VA., even though it was geographically closest to the tripped generator.

3. Simulations of the Frequency Measurements

The simulation data of the U.S. eastern interconnected system consist of 16,016 buses, 2,626 generating units, 12,188 loads, and 27,277 branches. Also, its total generating active power is assumed to be about 590,793MW, and total active power load is assumed to be approximately 583,374 MW. For simulating the measured events, buses matched to the locations of the tripped generators were confirmed in the system model as shown in Table A.1.In addition, buses matched to the locations of FDR units were confirmed to monitor the power system frequency during the simulation. After a search of the U.S. grid map from NERC, the buses matched to the locations of FDR units were found in the simulation data as shown in Table A.2. Although the FDR units were actually connected at power outlets in offices, the error caused by using buses on the transmission system as the locations of FDR units would be negligible since power system frequency is not changed through transformers. The latitude and longitude of the location of FDR units were used to select the matched buss in the simulation data.

The power system frequency excursion propagating from the location of the tripped generator would be detected as the sudden change of frequency at each monitoring point. In FNET, a certain threshold is adopted for determining if a frequency excursion arrives at an FDR unit. After considering the signal noise, equipment accuracy, and a reasonable safe margin, currently this threshold value is set to be 5mHz0. Since the sampling rate of FDR unit is higher than 1440Hz, the threshold of 5mHz is large enough to be used for analyzing FNET measurement0.To simulate the events as close as the FNET measurement, the same threshold is applied to detect the frequency drop at monitoring points in the simulation. Fig. 1 briefly shows how the detection time of the frequency drop is determined in the simulation results.

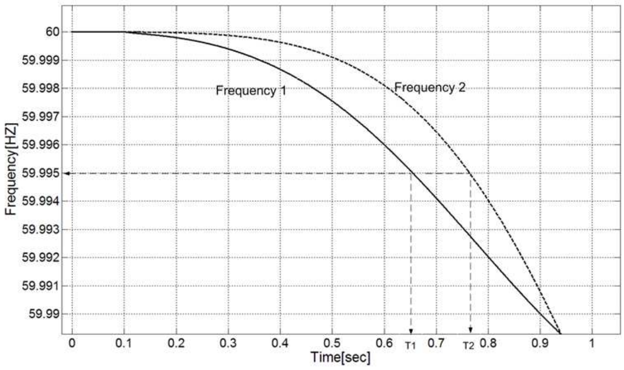


Fig. 1. The frequency drop detection time at each monitoring point

Table 4. Detection sequence and distance of monitorring points from the event location in the simulation results

Event		Freq. Drop Detection Sequence of monitoring pts. and their distances from the tripped Gen								
#1	Monitor #	4	3	6	2	7	9			
	Distance [mi]	328	365	458	510	631	820			
#2	Monitor #	7	4	2	6	3	11			
	Distance [mi]	272	269	419	346	485	438			
#3	Monitor #	7	2	4	6	3	11			
	Distance [mi]	134	369	411	474	630	589			
#4	Monitor #	4	11	3	6	2	7			
	Distance [mi]	253	287	405	384	389	437			
#5	Monitor #	7	2	9	4	6	3	11		
	Distance [mi]	134	369	420	411	474	630	589		
#6	Monitor #	20	7	2	4	9	6	11	3	
	Distance [mi]	176	212	254	405	549	501	468	611	
#7	Monitor #	4	11	3	6	2	20	7	9	
	Distance [mi]	238	283	383	371	412	271	457	654	
#8	Monitor #	9	20	6	7	4	17	3	2	11
	Distance [mi]	236	219	270	396	301	504	488	658	504

The simulation is based on the system response to the generation trip in the time domain. By tripping the same generators as confirmed in FNET measurement, and monitoring frequencies at the same locations as FDR units, the recreating simulations wereconducted.

In such simultions, the frequency at all measuring points is 60Hz before the event and the time delays also show up among frequency drops at different monitoring buses during the transient period. To compare the simulation results with the FNET measurements, frequency is plotted only at the monitoring buses where the FDR units could record the frequency at each event. Table 4 summarizes monitoring points in the sequence of detecting frequency drop and also shows the distances from the locations of the tripped generators to monitoring points.

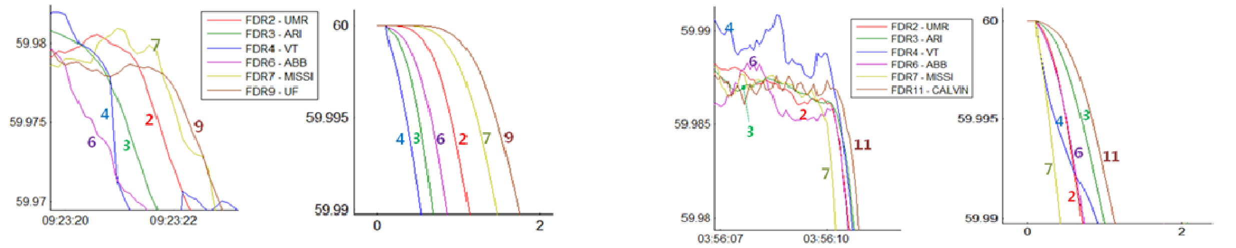
4. Comparison of Measurements and Simulations of Frequency

In comparing measurement with simulation of frequency responses, the measured frequency is not at the rated value even before the transient period and the shape of the frequency recovery is also different from the simulation result. The measurement data shows a frequency drop that never recovers, while its simulation shows a smaller drop followed by a recovery.

There can be various reasons, such as governor's performance or the load model, why the shape of the frequency response is different in the measurement and its recreating simulation. However, this paper focuses on finding any similarity between the measurements and the simulation of frequency responses. Fig. 2 shows a detailed comparison between them, and the curves of the same number indicate the frequency at the same locations in each case. In Fig. 2, the vertical axis represents the frequency in hertz, and the horizontal axis represents time in the coordinated universal time for the measurement and in seconds for the simulation respectively.

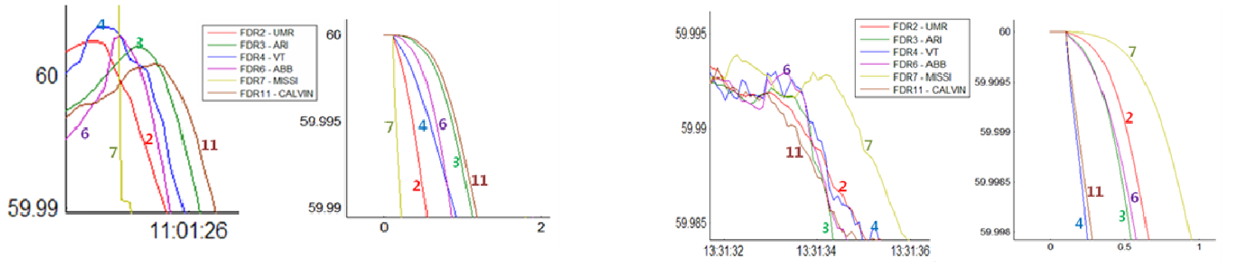
Although the overall shapes of the frequency responses to the same generator trips are different in the measurement and its simulation, the detection sequence of frequency drop seems to be matched quite well.

Here, to quantify the similarity in the detection sequence of the frequency drop between the measured data and their simulation result, a comparison index is proposed. Since the similarity should be analyzed not only by the detection sequence of monitoring points but also by the time difference(Δt) between them, the proposed comparison index quantifies both properties. To do this, the FDR units in the measurement and the monitoring points in the simulation are aligned in the sequence of detecting frequency drop, and the detection time is converted into the time difference(Δt) from the first detection unit. And, then the comparison index is calculated between the measured



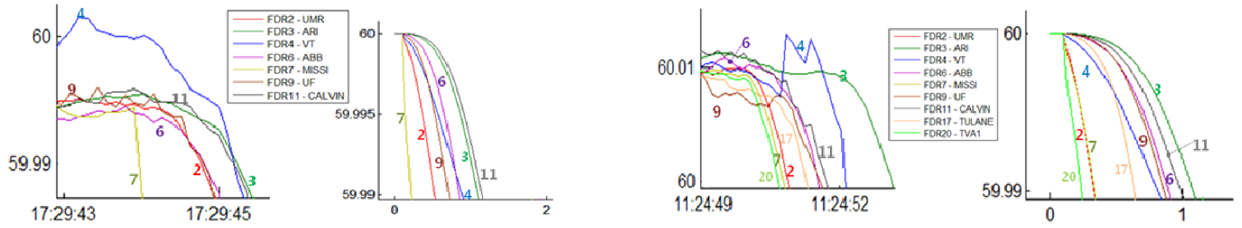
2-a. Event 1

2-b. Event 2



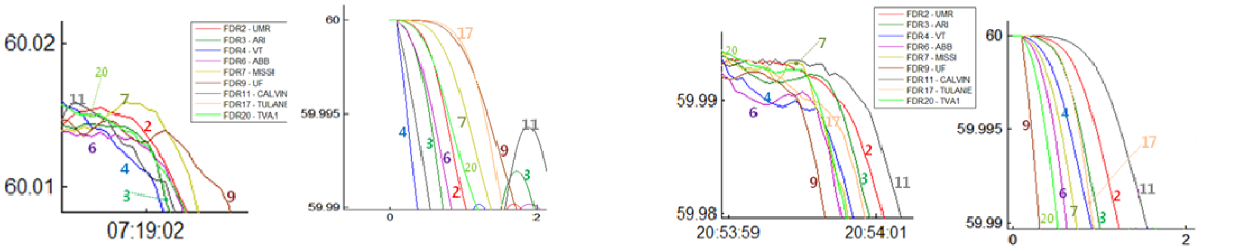
2-c. Event 3

2-d. Event 4



2-e. Event 5

2-f. Event 6



2-g. Event 7

2-h. Event 8

Fig. 2. Frequency Response Comparison

data and simulation results as defined in Eq. (1).

$$\text{Comparison Index} = \sqrt{\sum_{i=1}^{k}\sum_{j=i+1}^{k}[(\Delta t_{m,i} - \Delta t_{m,j}) - (\Delta t_{s,i} - \Delta t_{s,j})]^2} \quad (1)$$

where k is the number of the monitoring points, $\Delta t_{m,i}$ is the detection time difference of the ith FDR unit in the measurement data, and $\Delta t_{s,i}$ is the detection time difference of the i$^{\text{th}}$ monitoring point in the simulation result. In calculating the comparison index between the compared cases, the detection time from the respect of every monitoring point is compared each other and those differences between the measurement data and the simulation results are accumulated. Since the matrix of which elements are the detection time from the respect of every monitoring point($\Delta t_{i,j} = \Delta t_i - \Delta t_j$) is symmetric and its diagonal elements are zero, only its upper off-diagonal elements are calculated as defined in Eq. (1). Since a smaller value of the comparison index means the compared cases are more similar, the comparison index of two identical cases will become zero. Table 5 shows the calculated comparison indexes of every simulated result to each measured case. For example, in the measured case #1(Davis Besse), each simulation result(#S1~#S8) is compared with the measured data by calculating its comparison index and the comparison index appears to be the smallest with its recreating simulation case(#S1) as shaded in table .

As shown in Table 5, the comparison index of the measurement data appeared as the smallest with its recreating simulation except for the case 4. In Case 4, where the comparison indexes of other two simulated cases (1,7) are calculated to be similar to that of the recreating simulation case(4), the locations of the tripped generators in case S1 and S7 are also close to the location of the tripped generator in case 4. Therefore, the relative similarity in detection sequences of the frequency drop between frequency measurements and the recreating simulation results are verified. Since the major generating plants are usually located sparsely in US-Eastern Interconnected system, such a relative similarity between the wide-area power system frequency measurement and its recreating simulation could be found even with the limited accuracy of the dynamic model of power system.

Table 5. Calculated Comparison Indexes of simulation cases for each measured case

Simulation Cases / Measured Cases		S1	S2	S3&5	S4	S6	S7	S8
1	Davis Besse	0.557	9.291	13.821	0.834	12.13	0.801	12.309
2	Watts Bar	10.163	0.105	1.022	1.278	6.643	9.821	6.598
3	Browns Ferry	20.823	1.471	0.494	20.727	1.676	15.75	3.815
4	East Bend	3.352	13.382	18.486	3.767	16.599	3.673	12.282
5	Browns Ferry	25.662	1.247	0.506	1.546	20.739	25.568	20.331
6	Cumberland	20.624	7.303	9.472	21.199	6.816	15.482	14.124
7	Zimmer	4.091	10.709	15.315	4.328	11.773	1.684	18.231
8	Votgle Wilson	37.702	4.357	6.554	35.337	8.719	28.854	1.421

5. Conclusion

In this paper, actual wide-area power system frequency excursion measured by FNET was analyzed in detail, and it is simulated with the same event using the dynamic model of US Eastern Interconnected power system. By comparing frequency measurements with its simulation results to the same disturbances in very detail, the similarity could be found in the sequence of FDR units detecting the frequency excursion during the transient period. The similarity could be verified using the comparison index proposed to quantify the similarity of the compared cases in this paper. From findings in this paper, the simulation results are expected to compensate for the lack of the FNET measurement to the specific event in its applications in terms of the frequency drop detection sequence of FDR units.

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Appendix

Table A.1 Locations of the tripped generators in the simulation model

Event#	Plant Name	Plant Locations	
		Bus Name	BUS #
1	DavisBesse	DAV-BE	21630
2	Watts Bar	WBN	4197
3	Browns Ferry	BFN	4036
4	East Bend	EBND	25909
5	Browns Ferry	BFN	4036
6	Cumberland	CMB	4067, 4068
7	W H Zimmer	ZIMRLP	25925, 25926
8	Wilson	VOGTLE	15102

Table A.2. Locations of FDR units in the simulation model

FDR ID#	1	2	3	4	6	7	9	11	17	20
FDR NAME	NY	UMR	ARI	VT	ABB	MISS	UFL	Calvin	Tulane	TVA1
BUS Number	78782	96078	14132	22567	10117	98809	43159	28196	98652	652

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