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Wide-area Frequency-based Tripped Generator Locating Method for Interconnected Power Systems

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Abstract – Since the Internet-based real-time Global Positioning System(GPS) synchronized wide-area power system frequency monitoring network (FNET) was proposed in 2001, it has been monitoring the power system frequency in interconnected United States power systems and numerous interesting behaviors have been observed, including frequency excursion propagation. We address the consistency of a frequency excursion detection order of frequency disturbance recorders in FNET in relation to the same generation trip, as well as the ability to recreate by power systems dynamic simulation. We also propose a new method, as an application of FNET measurement, to locate a tripped generator using power systems dynamic simulation and wide-area frequency measurement. The simulation database of all the possible trips of generators in the interconnected power systems is created using the off-line power systems dynamic simulation. When FNET detects a sudden drop in the monitoring frequency, which is most likely due to a generation trip in power systems, the proposed algorithm locates a tripped generator by finding the best matching case of the measured frequency excursion in the simulation database in terms of the frequency drop detection order and the time of monitoring points.

Keywords: Power System Frequency Monitoring Network (FNET), Wide-area frequency, Tripped generator, Synchronizing power coefficient, Dynamic grid model, Matching algorithm

1. Introduction

Electric power systems have been operated based on the competitive electricity market where various interesting parties participate. Moreover, a renewable portfolio standard requires the increased production of electric energy from renewable energy sources which are intermittent by nature. With power systems facing the highest demand for a more intelligent operation than ever before, the wide-area monitoring of interconnected power systems is crucial. In the case of largely interconnected power systems like those of the United States, system operators need to recognize the system disturbances occurring in their own control areas, as well as in non-controlled systems which can affect each other.

The Internet-based real-time GPS synchronized wide-area power system frequency monitoring network (FNET) was proposed to monitor power system frequency more correctly and economically, and to indicate the balance of electric power across the nation grid 0. In monitoring the wide-area power system frequency of the U.S. power grid 04], interesting characteristics such as frequency wave, frequency drop propagation speed, and dependency on power flow directions have been observed from the frequency measurement [5-9]. Various applications have also been studied [8-12]. Among these applications, location estimation of the tripped generator covering all interconnected power systems is one of the most promising outcomes [13-15]. A sudden generator trip is one of the major disturbances in the power grid, and this can result in wide-area blackout as generally experienced. The power imbalance resulting from an unexpected generator trip produces an instant system frequency drop. The impact propagates from the location of the tripped generator to the other parts of the system through the electrical connections. This frequency propagation could be observed by frequency disturbance recorder (FDR) units widely deployed in the U.S. power grid. Under a competitive electricity market, utilities are not required to divulge all the information. Thus, system operators would benefit from recognizing a tripped generator occurring in non-controlled systems without the need to install high-cost facilities. System operators would save time and effort in analyzing the frequency excursion, which can be used for solving any dispute related to power system frequency in an electricity market.

Based on this characteristic, various algorithms have been proposed to estimate the location of a tripped generator using the measured frequency. These algorithms include the decision tree method, half-plane method, least square method, and non-linear method. The least square method has been employed to estimate event locations in

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the FNET server 0. The combined methods of these algorithms is expected to increase the accuracy of locating the tripped generator [13-15].

We introduce a new method to estimate the location of a tripped generator using a dynamic grid model-based simulation as well as frequency measurement. In the analysis of FNET measurement accumulated for several years, the frequency drop detection order of FDR units was quite consistent in relation to the same generator trip which occurred multiple times. The recreated simulation using the dynamic grid model also showed similarity in the frequency drop detection order. Therefore, in the simulation database of all the possible trips of generators created using the grid dynamic model, the proposed algorithm can find the best matching case of the measured frequency excursion in terms of the frequency drop detection order and the time of monitoring points. The proposed matching algorithm is expected to compensate for the inaccuracy of the grid model because the generators are located sparsely across the national grid. To some extent, the system operator can recognize which generator has caused the frequency excursion. The proposed algorithm is verified by applying it to the frequency drop cases measured by FNET and confirmed by the utilities to determine if the tripped generator can be pinpointed. The proposed method is expected to monitor and recognize grid events occurring outside of their control areas efficiently.

2. Detection order of frequency drop propagation

In FNET, the FDR plugged in a typical office outlet in each local area measures a local frequency synchronized by the GPS and sends it to a central server through the Internet 03]. The FDR developed for the FNET can be easily deployed with minimum cost. To date, more than 40 FDRs are deployed across U.S. interconnected power systems to cover all regional reliability regions that form the North American Electricity Council (NERC) in the US, and this number is still increasing [4].

As the propagation of the frequency drop caused by a tripped generator in the power grid during the transient has been observed in FNET, interesting characteristics could be recognized in the analysis of frequency measurements and its simulations. Fig. 1 shows an example of the frequency measurement during the transient and in cases where frequencies are different at different FDR locations.

Fig. 1 shows recreated simulation results of the FNET measurement when a generator is tripped in the north eastern area of the U.S. grid. These images are captured at 1, 3, and 6 seconds after a generator is tripped in the recreated time simulation.

When a generator is suddenly tripped in the power grid, the active power becomes unbalanced for a moment and its impact is shared by other synchronous machines according to their synchronizing power coefficients with respect to

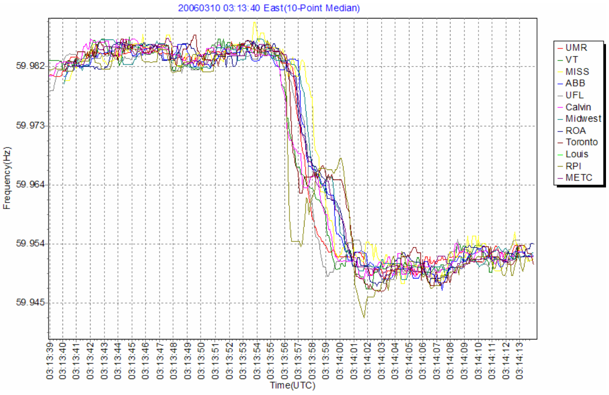
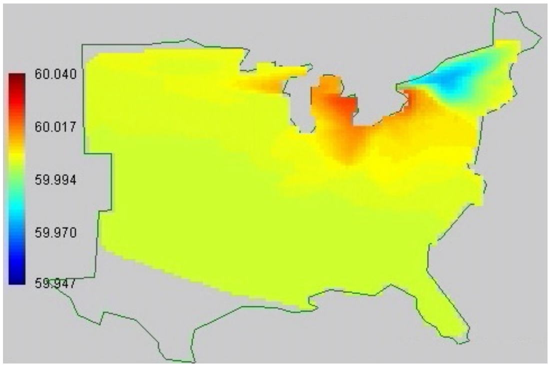
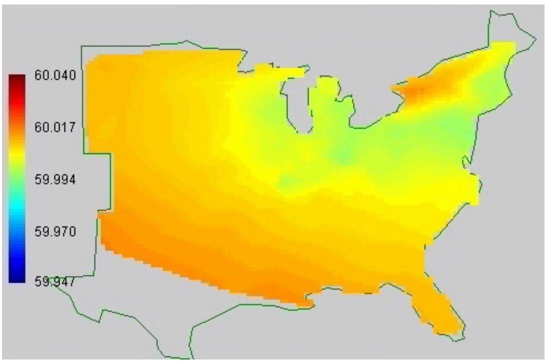


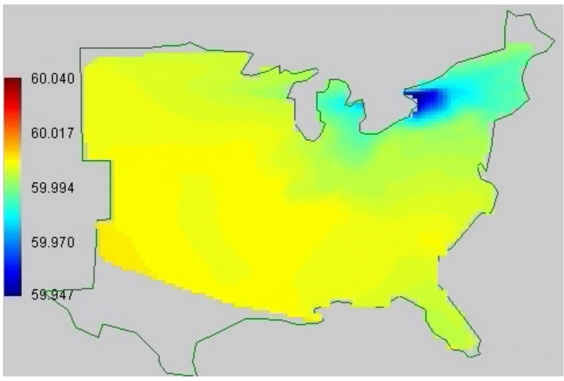
Fig. 1. Example of FNET measurement



(a) t=1 second after a fault



(b) t=3 seconds after a fault



(c) t=6 seconds after a fault

Fig. 1. Frequency drop propagation in the recreated simulation

the tripped generator [9, 17]. The synchronizing power coefficient of machine i to machine j is represented in Eq. (1) [17]

$$P_{sij} \cong \left.\frac{\partial P_{ij}}{\partial \delta_{ij}}\right]_{\delta_{ij0}} = E_i E_j (B_{ij}\cos\delta_{ij0} - G_{ij}\sin\delta_{ij0}) \tag{1}$$

where E_i is a constant voltage behind transient reactance for machine i, $G_{ij} + jB_{ij}$ is an element of the network admittance matrix Y, and δ_{ij0} is the initial angle difference between machine i and j ($\delta_{ij0} = \delta_{i0} - \delta_{j0}$). Since the synchronizing power coefficients represent the electrical distances between generators, the frequency drop would be detected earlier by FDRs electrically closer to the tripped generator. This also facilitates the frequency drop propagation from the location of the tripped generator. The propagation speed of the frequency drop would vary depending on the operating conditions of the power grid because the synchronizing power coefficients depend on the direction and the amount of power flows [9]. However, in the detailed analysis of FNET measurements and simulation results from recreating the FNET measurements, the order of monitoring points detecting such frequency drop appeared quite consistent to the order of the same generation trip even though it occurred at a different time. This section presents the repeatability of the frequency drop detection order of FDR units to the same generator trip in FNET measurements, and shows the similarity of the measurements with the recreated simulation results through comparative analysis. These findings are keys for the proposed algorithm in locating the tripped generator using FNET measurement.

2.1 Repeatability of the frequency drop detection order in FNET measurement

The time differences among FDR units detecting the frequency drop vary depending on the operating conditions of the power grid even if the same generator is tripped, because the electric distances between the tripped generator and the monitoring points are dependent on the operating conditions of the power grid [18]. However, as shown by the detailed analysis of the recorded cases in FNET measurement, the order of FDR units detecting the frequency drop appeared to be consistent enough to enable the identification of the tripped generators since the generators are located sparsely across the interconnected power systems.

Table 1 and Table 2 show the orders of the FDR units detecting the frequency drop of the same generation trip measured in FNET for several years. Common FDR units which could record multiple cases were compared separately because not every FDR unit was working in the selected cases. Only a few cases could be confirmed as the repeated trip of the same generator in the FNET database because every disturbance measured in FENT could not be confirmed by utilities and generators are not tripped very often in the power grid. Note that the measurements were randomly selected to serve as examples, and these were not related to any characteristic of the generators.

Table 1. Frequency drop detection orders of FDR units to the generation trip at Cumberland TN

Number	With all FDRs	Only with common FDRs
1	20→2,7→17→4,6,9,11→3	20→2,7→4,6,9,11→3
2	20→7→2,4→6→17→3,9→11	20→7→2,4→6→3,9→11
3	2,7,15,20→6,9,11,22→3	2,7,20→6,9 →3
4	7→2,9→22,26→13→3→11,28	7→2,9→3→11
5	2→4,6,9,13,22→11,18→3→27	2→4,6,9→11→3
6	2,7→6,33→4,9→23,35→28 →11→36→24→27	2,7→6→4,9→→11
7	17→30→36→2,7,15→32→9 →6,11,23,28	2,7→9→→6,11
8	15,32,36→7→2→23→ 4,9,11,28,30,35→24	7→2→→4,9,11

Table 2. Frequency drop detection orders of FDR units to the generation trip at Zimmer, OH

Number	With all FDRs	Only with common FDRs
1	4→11→3,20→6→2→7→9	4→11→3,20→6→2→7→9
2	13→11→2→20→7	11→2→20→7
3	4→11,28→22→→6→2,7,15,17	4→11→6→2,7
4	13→22→11,28→15,17 →2→7→9,27	11→2→ 7→9

In Table 1 and Table 2, FDR units are indicated with their ID numbers representing their locations shown in Table 3.

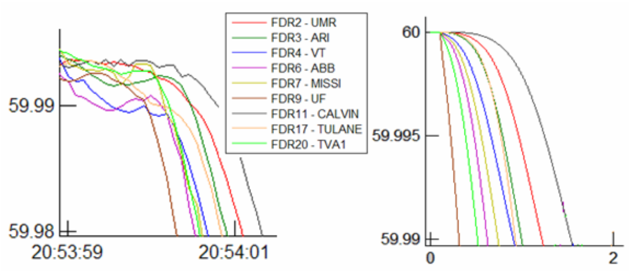
Table 3. ID numbers and names of FDR units

FDR ID	FDR name	FDR ID	FDR name	FDR ID	FDR name
1	Louisville	11	Calvin	22	ROA
2	UMR	12	Houston	23	FSU
3	ARI	13	Midwest ISO	24	Toronto
4	VT	14	ASU	26	Gen3 Birmingham
5	Seattle	15	TVA3 _Nashville	27	RPI
6	ABB	16	LA	28	METC
7	MISSI	17	TVA4 _Jackson	29	TAMU
8	EPRI	18	NY	31	Univ. of Kentucky
9	UFL	20	TVA2 _Huntsville	33	Univ. of Tennessee
10	TVA1 Chattanooga	21	WSU	35	ISU

Direct comparison of detection orders measured for the same generator trip is difficult because some FDR units stopped working temporally and did not send the locally measured data to the server. Comparing only the cases with common FDR units as shown in the last columns of Table 1 and Table 2 would be helpful to recognize the repeatability of the frequency drop detection order of FDRs. Detection orders of frequency drop to the same generator trip are slightly different in some cases. However, these are consistent enough to allow differentiation of the detection order to a specific generation trip because generators are located sparsely in the power grid.

2.2 Similarity between the measurement and the recreated simulation

Although FNET has been monitoring the U.S. power grid continuously for several years, the number of disturbances detected by FNET and confirmed by power utilities is very limited. Therefore, the grid dynamic model-based power system simulation was used to help us understand the dynamic behavior of wide-area power system frequency and verify the proposed FNET applications. While recreating the actual disturbances measured by FNET using the dynamic model of the U.S. power systems was conducted to verify the simulation model and understand the measured frequency data, an interesting similarity was found between the measured frequency and the simulated frequency. Fig. 2 compares the power system frequencies measured in FNET with the recreated simulation results.



<Measurement> <Simulation>

Fig. 2. Frequency measurement vs. simulation

In recreating the measured frequency distortion, the same generator is tripped and the same locations are monitored in the dynamic simulation as it occurred in the real systems. In both measurement and simulation (Fig. 2), the power system frequency appears to be different at different monitoring points during the transient. The frequency drop propagates from the tripped generator to the other parts of the power grid. Likewise Fig. 2 shows that although simulated frequency is not identical to the measured frequency as expected, the order of monitoring points detecting the frequency drop is very similar between the measurement and simulation.

In the FNET database, seven disturbances confirmed as the tripped generators were selected (Table 4). Recreating simulation was conducted using the U.S. eastern power system model. Similarly, these cases were randomly selected from the FNET database as examples.

Table 4. Tripped generators in the FNET database

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

Table 5 compares frequency drop detection orders of FDR units in the measurements and the monitoring points in the recreated simulation. Detailed data of the FNET measurement and simulation results are provided in Table A.1–Table A.7 of the Appendix.

Table 5. Comparison of the frequency drop detection order

Case	Tool	Detecting Order of FDR units
1	M	4⇨6⇨3⇨2⇨7⇨9
	S	4⇨3⇨6⇨2⇨7⇨9
2	M	7⇨2⇨6⇨4⇨3⇨11
	S	7⇨4⇨2⇨6⇨3⇨11
3	M	7⇨2⇨6⇨4⇨3⇨11
	S	7⇨2⇨4⇨6⇨3⇨11
4	M	7⇨2⇨9⇨6⇨4⇨11⇨3
	S	7⇨2⇨9⇨4⇨6⇨3⇨11
5	M	20⇨7⇨2⇨9⇨6⇨11⇨4⇨3
	S	20⇨2,7⇨4⇨9⇨6⇨11⇨3
6	M	4⇨11⇨3⇨20⇨6⇨2⇨7⇨9
	S	4⇨11⇨3⇨6⇨2⇨20⇨7⇨9
7	M	9⇨7⇨20⇨6⇨4⇨17⇨3⇨2⇨11
	S	9⇨20⇨6⇨7⇨4⇨17⇨3⇨2⇨11

※ M: Measurement, S: Simulation

Although the detection orders shown in Table 5 slightly differ between the measurement and the recreated simulation, these are similar enough to match the measurement with its recreated simulation.

To compare the detection order more correctly using both the order and the time of frequency drop detection, the comparison index is proposed as Eq. (2).

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

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.

Since the comparison index would be smaller between more similar cases, its value will be zero for two identical cases. Table 6 shows the comparison indexes calculated for the eight cases described above. For each measured frequency, every simulation result was compared by calculating the comparison indexes to find the most similar case.

Table 6. Calculated comparison indexes of simulation cases for each measured case

M S	1	2	3	4	5	6	7
1	0.56	10.16	20.82	25.66	20.62	4.09	37.70
2	9.29	0.10	1.47	1.25	7.30	10.71	4.36
3&4	13.82	1.02	0.49	0.51	9.47	15.32	6.55
5	12.13	6.64	1.68	20.74	6.82	11.77	8.72
6	0.80	9.82	15.75	25.57	15.48	1.68	28.85
7	12.31	6.60	3.82	20.33	14.12	18.23	1.42

※ M: Measurement, S: Simulation

As marked in gray in Table 6, the comparison index of the measurement appeared to be the smallest compared with its recreated simulation. Therefore, matching the measured frequency with its recreated simulation by finding the most similar case in terms of the frequency drop detection order and time is feasible.

3. Tripped generator-locating

The frequency drop detection order appeared to be consistent with the same generation trip in FNET measurement. Since it could be recreated by the grid model based simulation described in Section 2, a new algorithm for locating a tripped generator in the interconnected power systems is proposed using the frequency measurement and simulation result. It would be feasible to recognize a tripped generator using the detection order and time of FDR units which measure a sudden drop in frequency if such frequency drop detection order and time of FDR units to a specific generation trip in power grid can be known in advance. However, because the actual cases of tripped generators accumulated in the FNET measurement database are very limited, the proposed method uses the dynamic grid model to create the database of all possible generator trips in the power grid off-line.

Fig. 3 shows the overview of the proposed method for locating a tripped generator. The details are described in Sections 3.1 and 3.2.

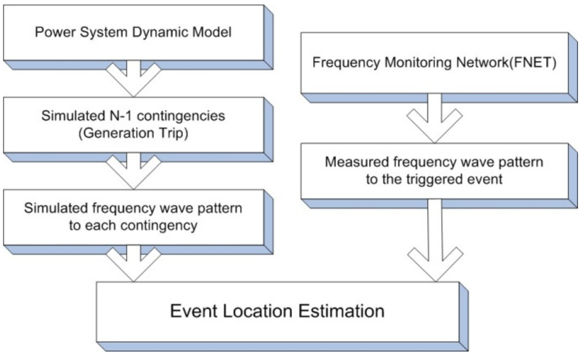


Fig. 3. Overview of the proposed algorithm

3.1 Simulation database of the generation trips

The simulation database needs to include the frequency drop detection results at all the FDR locations for every trip of generators. In the simulation data of the U.S. eastern interconnected system used in this study, there are 2,626 machines. Only one representative machine at each plant is considered in the development of the simulation database because one machine in the same plant will be enough to indicate the location of a tripped generator. The different rating of a tripped generator would not cause significant difference in locating a tripped generator because the proposed algorithm would be more dependent on the location of the tripped generator. In addition, because trips of small generators may not be of interest, only generators with capacities bigger than 500 MW are considered in creating the simulation database. The generation trip of 500 MW would drop the power system frequency by about 0.0172 Hz from the normal value considering the sensitivity characteristic between the frequency drop and the power imbalance in U.S. eastern interconnection found by FNET. Therefore, 353 units among 2,626 generators in U.S. eastern interconnection are considered. The frequency drop also needs to be monitored at the locations of all the FDR units during simulations. Through this, the frequency response measured by any FDR unit can be compared and will lead to the best matching case in the simulation database. In this paper, 26 FDR units deployed in North America are considered. To monitor the frequency response at the locations of FDR units in the simulation, the buses closest to the locations of FDR units are placed in the grid model using the latitude and longitude of the FDR unit. This was achieved after a tedious search on the U.S. transmission map.

Fig. 4 shows the buses on the grid map which represent the locations of FDR units as dots.

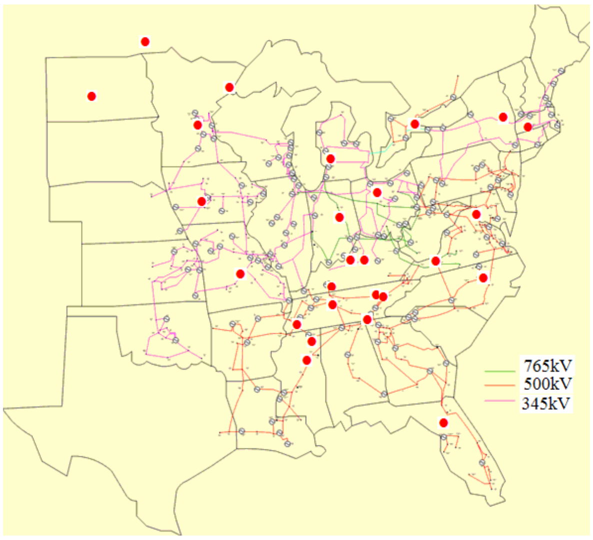


Fig. 4. Monitoring buses in the grid model

A total of 146 monitoring buses are also added to accommodate the increasing number of FDR units marked Θ in Fig. 4.

The simulation was conducted using the Power System Simulator for Engineering program. The frequency responses at all the 172 monitoring buses were recorded in each case.

Fig. 5 is an example of the simulated frequency responses of the 172 monitoring buses to a generation trip. In Fig. 5, a generator is tripped at 1 second and the simulation is conducted for 10 seconds, which is long enough to detect the frequency drop at the monitoring buses.

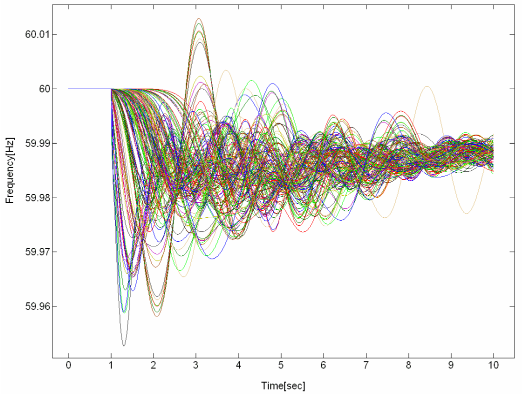


Fig. 5. Example of the simulated frequency

In creating the simulation database, the simulation results were processed to calculate the frequency drop detection time at every monitoring bus. The frequency drop detection time is defined as the time when the frequency at the monitoring bus drops more than a threshold value (8 mHz) from a normal value. This threshold value is adopted from the actual FNET equipment set to consider the signal noise, equipment accuracy and a safe margin. Although a different threshold value could change the frequency detection order to be used for locating a tripped generator, 8 mHz appeared to be small enough to minimize such impact in most cases. The proposed algorithm uses a relative similarity with the frequency drop detection order by applying the same threshold to both measurement and simulation.

Fig. 6 shows how the frequency drop detection time (T_1, T_2, T_3) at three monitoring buses was determined.

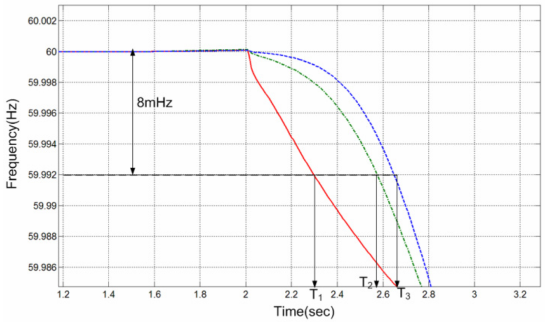
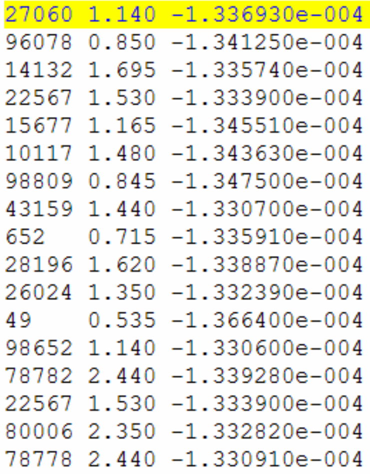


Fig. 6. Frequency drop detection time

Fig. 7 shows an example of the case file in the simulation database. In the data, the first column indicates the monitoring bus, the second column indicates the detection time at each bus in second, and the third column indicates the frequency deviation per unit at the detection time.



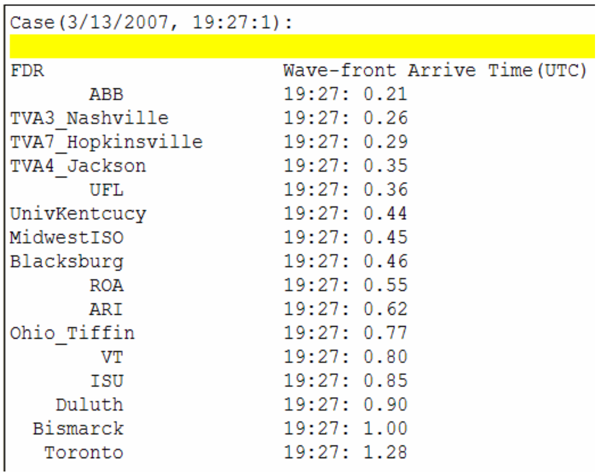
```
27060 1.140 -1.336930e-004
96078 0.850 -1.341250e-004
14132 1.695 -1.335740e-004
22567 1.530 -1.333900e-004
15677 1.165 -1.345510e-004
10117 1.480 -1.343630e-004
98809 0.845 -1.347500e-004
43159 1.440 -1.330700e-004
652   0.715 -1.335910e-004
28196 1.620 -1.338870e-004
26024 1.350 -1.332390e-004
49    0.535 -1.366400e-004
98652 1.140 -1.330600e-004
78782 2.440 -1.339280e-004
22567 1.530 -1.333900e-004
80006 2.350 -1.332820e-004
78778 2.440 -1.330910e-004
```

Fig. 7. Example of a case file in the simulation database

3.2 Matching algorithm of frequency measurements to simulation database

Based on the simulation database described in Section 3.1, the frequency drop measured in FNET is compared with each simulation case to find the best matching case that can indicate the most likely tripped generator. To achieve this, a matching algorithm is proposed.

When a generation trip is triggered by FNET, the frequency drop detection time at all working FDR units can be obtained. In Fig. 8, FDR units are indicated by their names and the frequency drop detection time is represented in Coordinated Universal Time (UTC).



```
Case(3/13/2007, 19:27:1):

FDR                     Wave-front Arrive Time(UTC)
       ABB              19:27: 0.21
TVA3_Nashville          19:27: 0.26
TVA7_Hopkinsville       19:27: 0.29
TVA4_Jackson            19:27: 0.35
       UFL              19:27: 0.36
UnivKentcucy            19:27: 0.44
MidwestISO              19:27: 0.45
Blacksburg              19:27: 0.46
       ROA              19:27: 0.55
       ARI              19:27: 0.62
Ohio_Tiffin             19:27: 0.77
        VT              19:27: 0.80
       ISU              19:27: 0.85
    Duluth              19:27: 0.90
  Bismarck              19:27: 1.00
   Toronto              19:27: 1.28
```

Fig. 8. Frequency drop detection time in FNET

In searching for the best matching case of the measured data in the simulation database, the first step is to create a subset of the database considering only the monitoring locations of working FDR units because some FDR units could stop working at the event.

After the subset of the database is prepared to match the measured case, the algorithm converts the frequency drop detection time at each monitoring location into the time difference (ΔT) from the first detection time in both the simulation database and the measurement. Together with the subset of the database and measured dataset which consists of the time differences, the matching algorithm starts to compare the measured case with every simulation case. Table 7 shows a conceptual example of the comparison between the measurement data set and the simulation case of the database.

Table 7. Searching for the best matched case of the measurement in the simulation database

Simulation database (subset)					⇔	FNET	
	G1	G2	....	G353		FDR	ΔT
M_2	ΔT(2,1)	ΔT(2,2)	....	T(2,353)		M_2	ΔT_2
M_4	ΔT(4,1)	ΔT(4,2)	....	ΔT(4,353)		M_4	ΔT_4
M_6	ΔT(6,1)	ΔT(6,2)	....	ΔT(6,353)		M_6	ΔT_6
· ·	· ·	· ·	....	· ·		· ·	· ·
M_{167}	ΔT(6,1)	ΔT(167,2)	....	ΔT(167,353)		M_{167}	ΔT_{167}
M_{168}	ΔT(6,1)	ΔT(168,2)	....	ΔT(168,353)		M_{168}	ΔT_{168}
M_{171}	ΔT(171,1)	ΔT(171,2)	....	ΔT(171,353)		M_{171}	ΔT_{171}
M_{172}	ΔT(172,1)	ΔT(172,2)	....	ΔT(172,353)		M_{172}	ΔT_{172}

In Table 7, $\Delta T(i,n)$ is ΔT at the i_{th} monitoring location to the n_{th} generation trip in the simulation database, and $\Delta T(j)$ is ΔT at j_{th} FDR unit in the measurement.

In the process of comparison, the cases compared after every time difference between all the monitoring points are recalculated based on the comparison tables of the simulated and measured data to ensure that all the monitoring points are compared. In the comparison table of the simulated data, the element $\delta_{s,n}(i,j)$ is the time difference [$\Delta T(i,n)$ - $\Delta T(j,n)$] between monitoring point *i* and *j* for the trip of the generator and *n* in the simulated case. In the comparison table of the measured data, the element $\delta_m(i,j)$ is the time difference [$\Delta T(i)$ - $\Delta T(j)$] between FDR units *i* and *j* in the measured case.

Using the comparison tables, the matching algorithm finds the best matched simulation case for the measured case by calculating the matching index defined as

$$\mathrm{n} = \sqrt{\sum_{i=1}^{k-1} \sum_{j=i+1}^{k} (\delta_{s,n}(i,j) - \delta_m(i,j))^2} \qquad (3)$$

where k is the number of FDR units that detect the frequency drop, $\delta_{s,n}(i,j)$ is the element of the comparison table for the simulated case, and $\delta_m(i,j)$ is the element of the comparison table for the measured case. This matching index considers the frequency drop detection order of monitoring locations and the time difference between the detections. The smaller the matching index of a specific generation trip, the higher the possibility that the generator is tripped.

4. Study Cases

In this section, the proposed method is verified by applying it to find a tripped generator using only FNET measurements recorded during the disturbances. The disturbances have been previously confirmed as generation trips by power utilities. In the summary in Table 8, 10 cases of generation trips accumulated in FNET measurements for several years were confirmed, and the simulation database which consists of 353 generation trip cases was created as described in Section 3.1. Cases 1–6 are the same cases described in Table 4. Detailed data of cases 7–10 are provided in Table A.8–Table A.11 of the Appendix.

Table 8. Generation trips measured in FNET

Number	Tripped generator	Date	Number of monitoring FDR
1	Davis Besse, OH	8/4/04	6
2	Watts Bar, TN	9/19/04	7
3	Browns Ferry, AL	2/11/05	7
4	Cumberland, TN	3/21/05	8
5	Zimmer, OH	4/22/05	8
6	Wilson, GA	4/29/05	8
7	Cumberland, TN	7/13/05	7
8	Cumberland, TN	7/7/06	12
9	Watts Bar, TN	7/31/06	9
10	Sequoyah, TN	3/13/07	14

To find a tripped generator using FNET measurements, the proposed algorithm calculated the comparison indexes between each of the simulated cases and each measured case. Subsequently, the algorithm sorted the simulated cases in ascending order according to their comparison indexes. The tripped generator of the simulation case ranked first in this order is thus an estimated generation trip which caused the measured frequency drop. Table 9 summarizes the results.

Table 9. Summary of the study case results

Number	Estimated location of Generator	Rank of the tripped generator	Error (miles)
1	Davis Besse, OH	1_{st}	0
2	Watts Bar, TN	1_{st}	0
3	Browns Ferry, AL	1_{st}	0
4	Cumberland, TN	1_{st}	0
5	J M Stuart, OH	78_{th}	25
6	Votgle, GA	1_{st}	0
7	Cumberland, TN	1_{st}	0
8	Cumberland, TN	1_{st}	0
9	Watts Bar, TN	1_{st}	0
10	Watts Bar, TN	2_{nd}	25

Table 9 shows that the algorithm could exactly pinpoint the tripped generators in 8 out of 10 cases. In the other two cases, the tripped generators were within 25 miles away from the generators identified by the algorithm. Furthermore, because there were more FDR units in the southern area of the U.S. grid (Fig. 5), it was deemed more correct to locate the tripped generator in the southern area. As more FDR units are deployed, the performance of the proposed algorithm is expected to improve.

Fig. 9 shows the locations of the generator identified through estimation and the actual generator that was tripped on the grid map.

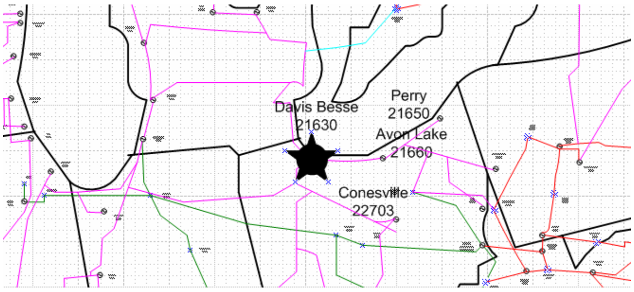


Fig. 9. Estimated location (★) and actual location (●) of the tripped generator (Case 1)

As shown in Fig. 9, the sparse locations of generators would be advantageous in finding the tripped generator in the proposed method.

In Case 5, although a nearby generator was estimated to be a tripped generator, it is only 25 miles away from the actual tripped generator (Fig. 10). Note that this can be still informative to system operators.

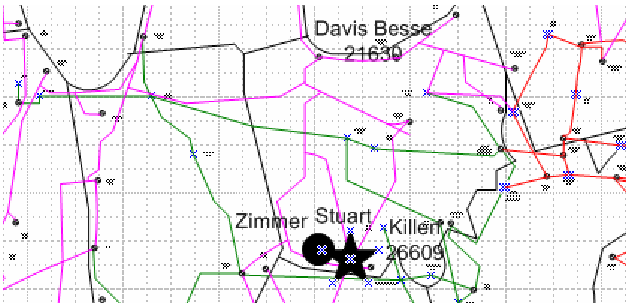


Fig. 10. Estimated location (★) and actual location (●) of the tripped generator (Case 5)

As shown above, the performance of the proposed method is very promising considering that only about 6–14 FDR units could be used in locating the tripped generators in the case studies. The performance can be considerably improved by increasing the number of the deployed FDR units that measure the frequency excursion during the transient. If multiple methods could be coordinated to estimate a tripped generator using the wide-area frequency measurement, its accuracy could be improved as well.

5. Conclusion

We proposed a new method for locating a tripped generator in interconnected power systems based on the wide-area frequency measurement and grid dynamic model. Intelligent operation of the interconnected power systems requires wider monitoring of the power grid. However, sharing information across interconnected power systems would be limited especially in the competitive electricity market. A sudden generator trip is one of the major disturbances in the power grid and is related to wide-area blackout. The proposed method can locate a tripped generator based on the sudden drop in power system frequency regardless of which control area the generator belongs to. This can be done by finding the best matching case of the measured frequency excursion in the simulation database in terms of the frequency drop detection order and time of the monitoring points. Since FNET measures power system frequencies from any power outlet at home or office, the accuracy of the introduced method can be improved by increasing the number of monitoring points in the FNET. The proposed method is applicable to the FNET in coordination with existing on-line algorithms.

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Appendix

Table A.1. Detection time in Case 1

FDR UNIT(#)	Detection Time [sec]	
	FNET	Simulation
UMR(2)	14:23: 9.49	0.894
ARI(3)	14:23: 9.24	0.506
VT(4)	14:23: 9.08	0.347
ABB(6)	14:23: 9.10	0.647
MISS(7)	14:23:10.04	1.210
UFL(9)	14:23:10.06	1.449

Table A.2. Detection time in Case 2

FDR UNIT(#)	Detection Time [sec]	
	FNET	Simulation
UMR(2)	8:55:58.53	0.494
ARI(3)	8:55:58.67	0.690
VT(4)	8:55:58.56	0.348
ABB(6)	8:55:58.54	0.500
MISS(7)	8:55:58.30	0.267
CALVIN(11)	8:55:58.82	0.826

Table A.3. Detection time in Case 3

FDR UNIT	Detection Time [sec]	
	FNET	Simulation
UMR(2)	16: 1:13.54	0.36
ARI(3)	16: 1:14.01	0.86
VT(4)	16: 1:13.81	0.57
ABB(6)	16: 1:13.66	0.65
MISS(7)	16: 1:12.94	0.14
CALVIN(11)	16: 1:14.14	0.91

Table A.4. Detection time in Case 4

FDR UNIT	Detection Time [sec]	
	FNET	Simulation
UMR(2)	22:29:32.85	0.36
ARI(3)	22:29:33.32	0.86
VT(4)	22:29:33.27	0.57
ABB(6)	22:29:32.96	0.65
MISS(7)	22:29:32.44	0.14
UFL(9)	22:29:32.92	0.53
CALVIN(11)	22:29:33.29	0.91

Table A.5. Detection Time in Case 5

FDR UNIT(#)	Detection Time [sec]	
	FNET	Simulation
UMR(2)	16:24:38.64	0.23
ARI(3)	16:24:39.26	0.86
VT(4)	16:24:39.17	0.55
ABB(6)	16:24:39.15	0.70
MISS(7)	16:24:38.60	0.23
UFL(9)	16:24:39.13	0.68
CALVIN(11)	16:24:39.16	0.77
TVA(20)	16:24:38.55	0.16

Table A.6. Detection time in Case 6

FDR UNIT(#)	Detection Time [sec]	
	FNET	Simulation
UMR(2)	12:18:50.11	0.76
ARI(3)	12:18:49.94	0.54
VT(4)	12:18:49.60	0.24
ABB(6)	12:18:50.06	0.59
MISS(7)	12:18:50.22	1.04
UFL(9)	12:18:50.44	1.33
CALVIN(11)	12:18:49.72	0.34
TVA(20)	12:18:49.96	0.80

Table A.7. Detection time in Case 7

FDR UNIT	Detection Time [sec]	
	FNET	Simulation
UMR(2)	1:53:48.69	0.96
ARI(3)	1:53:48.65	0.78
VT(4)	1:53:48.47	0.65
ABB(6)	1:53:48.41	0.47
MISS(7)	1:53:48.22	0.55
UFL(9)	1:53:47.99	0.22
CALVIN(11)	1:53:48.89	1.24
Tulane(17)	1:53:48.5	0.76
TVA(20)	1:53:48.37	0.38

Table A.8. FNET measurement on 7/13/05

FDR ID	FDR NAME	Detection Time
7	MISSI	5:53:13.72
2	UMR	5:53:13.74
15	TVA3_Nashville	5:53:13.75
9	UFL	5:53:14.13
6	ABB	5:53:14.17
11	Calvin	5:53:14.19
3	ARI	5:53:14.35

Table A.9. FNET measurement on 7/7/06

FDR ID	FDR NAME	Detection Time
7	MISS	13:26:24.13
2	UMR	13:26:24.15
10	TVA1_Charttanooga	13:26:24.53
6	ABB	13:26:24.59
13	Midwest ISO	13:26:24.61
4	VT	13:26:24.65
9	UFL	13:26:24.69
35	ISU	13:26:24.76
23	Duluth	13:26:24.78
11	Calvin	13:26:24.95
502	Toronto	13:26:25.47
27	RPI	13:26:25.54

Table A.10. FNET measurement on 7/31/06

FDR ID	FDR NAME	Detection Time
15	TVA3_Nashville	16:13: 8.91
17	TVA4_Jackson	16:13: 9.08
31	Univ. of Kentucky	16:13: 9.21
2	UMR	16:13: 9.49
9	UFL	16:13: 9.49
13	Midwest ISO	16:13: 9.53
4	VT	16:13: 9.56
27	RPI	16:13:10.14
502	Toronto	16:13:10.51

Table A.11. FNET measurement on 3/13/07

FDR ID	FDR NAME	Detection Time
6	ABB	19:27: 0.21
15	TVA3_Nashville	19:27: 0.26
32	TVA7_Hopkinsvill	19:27: 0.29
17	TVA4_Jackson	19:27: 0.35
9	UFL	19:27: 0.36
31	Univ. of Kentucky	19:27: 0.44
13	Midwest ISO	19:27: 0.45
3	ARI	19:27: 0.62
506	Ohio, Tiffin	19:27: 0.77
4	VT	19:27: 0.80
35	ISU	19:27: 0.85
23	Duluth	19:27: 0.90
43	Bismarck	19:27: 1.00
502	Toronto	19:27: 1.28

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