CPS: Breakthrough: Collaborative Research: WARP: Wide Area assisted Resilient Protection

Sukumar Brahma[1], Munim Bin Gani[1], Rajesh Kavasseri[2], Nilanjan R. Chaudhuri[3]

1 - New Mexico State University, Clemson University, 2 - North Dakota State University, 3 - Pennsylvania State University

PROBLEM/CONTEXT

One wrong move (misopearion) by a protective relay during stressed conditions can spell disaster for the power grid. Misoperations of relays cannot be detected in real time.

OVERARCHING GOAL

Can we detect and swiftly correct relay misoperations in real time to avert an impending cascade?

KEY IDEAS

- Supervise relay operation using *components* of energy function that provide event "fingerprints", calculated using wide-area measurement sets;
- Use Dynamic State Estimation (DSE) to calculate components of energy functions where direct measurements are not available (e.g., generators);
- Dynamic simulation of a historic blackout to create test-data. Simulated data should be verified using field data available in blackout report/log.
- Use realistic wide-area simulation data to test all proposed theories related to energy functions and communication.

APPROACHES

- Software Platform- PSLF (Positive Sequence Load flow)
- Data Reference- "Arizona-Southern California Outages on September 8, 2011: Causes & Recommendations"; Prepared by FERC & NERC
- Steady State Simulation:

1. System Description file- 2010 Heavy Summer Demand (10HS3B.epc) as an starting point
2. Matching the generation, load and net interchange data in the blacked out areas available from the data reference.
3. Power Flow solution file developed in step 2 closely represents the healthy system just before the initiation of blackout. It worked as the base file for dynamic simulation.

- Dynamic simulation of blackout:

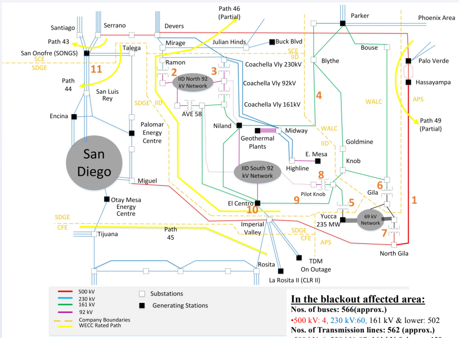
1. Dynamically simulate the whole event and match the power flows and voltages in simulation with blackout event provided in data reference.
2. Calculating relay settings from data reference and WECC standard. Inserting relay models and tripping transmission facilities according to reported relay operations (Table 1).

- Transmission Line Energy function (W_{25}) calculation:

1. Construction of W_{25} for area under IID throughout the blackout event. (Fig. 4)
2. Comparison of W_{25} values under load encroachment and actual fault scenarios. (Table 2)

Simulating September 8, 2011 Arizona-Southern California Blackout

Fig.1- Overview of the affected power system



In the blackout affected area:
Nos. of buses: 566(approx.)
•500 kV: 4, 230 kV:60, 161 kV & lower: 502
Nos. of Transmission lines: 562 (approx.)
•500 kV: 6, 230 kV: 97, 161 kV & lower: 459
Nos. of transformers: 246 (approx.)
Nos. of generators: 156 (approx.)

Summary of Events:

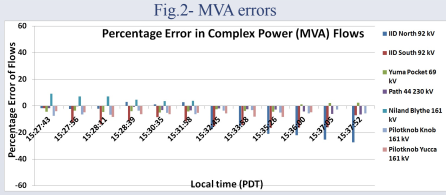
Affected elements are numbered in fig.1, and described below:

- At 15:27:39, Hassayampa-North Gila (H-NG) 500 kV line tripped. (carrying approx 1400 MW to southern San Diego) – [#1]
- Redistributed flows through Imperial Irrigation District (IID) network (parallel in nature with H-NG) caused to trip IID's northern transmission resources namely Ramon 230/92 kV transformer [#2], Coachella Valley 230/92 kV transformer [#3], Blythe-Niland 161 kV line [#4] by 15:32:13 - **4 min. 34 s.**
- After that, the flows redistributed through Yuma area load pocket and eventually tripped Yucca 161/69 kV transformers [#5] and Gila 161/69 kV transformers [#6] by 15:36:40, leaving Yuma load pocket to draw power through N.Gila 500/69 kV transformers [#7] only – **9 min. 1 s**.
- Increased flows caused Pilotknob 161/92 kV transformers [#8] and Pilotknob-Elcentro 161 kV line [#9] (Z-3 operation due to load encroachment) to trip. This left IID with only one transmission source- ImperialValley-Elcentro 230 kV (S) line [#10]. S line tripped on 15:38:02 creating IID island – **10 min. 33 s**.
- The aforementioned events were gradually increasing the current in Path 44 [#11]. The current finally reached 8700 amps- enough for tripping (>8000 amps) Path 44. Path 44 tripped at 15:38:21, causing the San Diego island. Frequency in the island dropped rapidly and the generators and loads tripped eventually – **10 min. 52 s to Blackout.**

Error result from the comparison between simulated and actual flows in key lines

We made the comparison of the flows from the simulation at **13 different time stamps** as provided in the report. The errors are plotted below:

Fig.2- MVA errors



Observations:

• The simulated result shows close proximity with the actual data. The final average error for the flows are:

$$Error_{MW} = 9.12\%$$
$$Error_{MVAR} = 14.46\%$$
$$Error_{MVA} = 8.27\%$$

Fig.3- Comparisons between actual voltage and simulated voltage

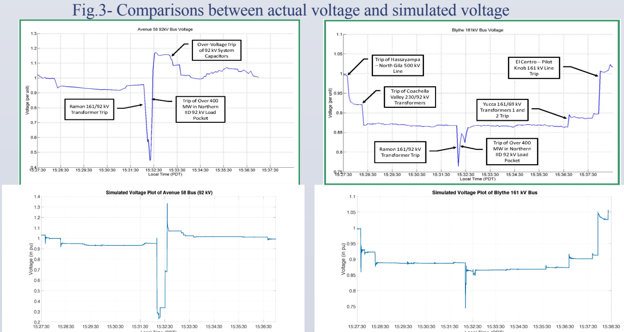


Fig. 4- Energy Function W25 in IID Until Islanding

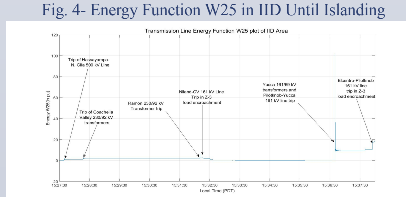


Table 1: List of Relay Operations

SN	Equipment Name	Reported Relay Operation
1	Hassayampa-N.Gila 500 kV line	High speed protection System operated. No specific relay operation reported.
2	Generator at La Rosita	May have been triggered by transients. No specific relay operation reported.
3	Coachella Valley 230/92 kV Transformers	Overcurrent Relay (IDMT)
4	Ramon 230/92 kVTransformers	Overcurrent Relay (IDMT)
5	Blythe-Niland 161 kV Line	Overcurrent Relay (IDMT)
6	Niland-CV 161 kV line	Distance Relay (Z-3 load encroachment)
7	Multiple Generators connected at IID's 92kV System including Niland Gas Turbine 2, CV Gas Turbine 4, Independent power Producer Colmac's unit, Drop 4 unit 2 Hydro generator	Loss of IID's Northern resources and subsequent system response caused loss of these generators. No specific relay operation reported.
8	444 MW of IID's load	Under Voltage Load shedding relay
9	Gila 161/69 kV Transformers	Overcurrent Relay (IDMT)
10	Yucca 161/69 kV Transformers	Overload relay
11	Pilotknob-Yucca161 kV line	Transfer trip from Yucca 161/69 kV transformers' overload relay
12	Yuma combined cycle Generator at 69kV	Cause of the trip is unknown. No specific relay operation reported.
13	Pilotknob 161/92 kV Transformers	Overload relay
14	Elcentro-Pilotknob 161 kV Line	Distance Relay (Z-3 load encroachment)
15	Buck Boulevard Combustion turbine Generator	RAS operation
16	Two combustion turbine generators at Central La Rosita in Mexico	RAS operation
17	Imperial Valley Elcentro 230 kV S line	RAS operation
18	WECC PATH 44	Overcurrent Relay (IDMT)

Achieved Relay Operations from Table 1 in Simulation

- **Distance Relays**: SN#1 was tripped by distance relay model after creating a fault near N.Gila end. Zone-1 tripping from the N.Gila end and Zone-2 tripping from Hassayampa end was achieved. For SN#6 &14 -Distance relay models were implemented following standard practice. However, the relays did not trip on load encroachment during simulation. These relays were tripped through script.
- **Overcurrent and overload relays:** Trippings listed in SN#3, 4, 5, 9, 10, and 13 were achieved inserting overcurrent relay models with settings calculated from [1]. For SN#18, no relay model is available to supervise summation of current in multiple lines. So, those lines in PATH 44 were tripped by script.
- **Under Voltage Relays:** Loads and generator tripping listed in SN#7 & 8 were achieved by undervoltage relay models. Their settings have been calculated according to the WECC guidance for UVLS and NERC guidance for under voltage generator tripping.
- **Others:** The RAS operations in SN#15, 16, 17 and transfer trip in SN#11 have been implemented through scripting. Station "Drop 4" unit 2 in SN#7 and generator tripping in SN#2 & 12 were done by script also.

Comparisons of W_{25} under Different Scenarios

Table 2: Change in W_{25} under load encroachment and faults

Facility Name	Change of W_{25} (in pu) under			
	Load encroachment	Zone-1 fault	Zone-2 Fault	Zone-3 fault
Niland-Coachella Valley 161 kV line	0.726	1.077	2.266	2.369
Elcentro-Pilotknob 161 kV Line	7.5	7.64	7.82	8.22

Observations from Table 2

- ΔW_{25} is higher in general for fault than for a load encroachment event. So it is evident that W_{25} is more sensitive to system faults.
- Though ΔW_{25} is changing more under fault conditions for those two load encroachment events, from figure 4 it can be seen that there were other events when some transmission facilities got tripped under overcurrent and ΔW_{25} was much higher than the load encroachment events. So, the proposed measure to uniquely detect faults using changes in W_{25} is not successful, though it worked well for a smaller benchmark system described in [2], [3].

Future Work

1. Further research will be done to check if W_{25} along with other measures can detect faults.
2. Implementing other components of energy functions in the simulated test-bed to examine their response.
3. Archive the simulation data and disseminate.

Acknowledgements

The PIs gratefully acknowledge NSF grants CPS#1544621 (at NDSU) and CPS#1544645 (at NMSU), #1855854 (at Clemson).

References

1. Report prepared by the Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC), "*Arizona- Southern California Outages on September 8, 2011: Causes and Recommendations*", https://www.ferc.gov/legal/staff-reports/04-27-2012-ferc-nerc-report.pdf
2. Yinan Cui, Rajesh Kavasseri, Sukumar Brahma, "A New Approach for Event Detection Based on Energy Functions," Proc. IEEE PES General Meeting 2014, Washington, DC.
3. S. Brahma, R. Kavasseri, Huiping Cao, N. R. Chaudhuri, T. Alexopoulos, and Y. Cui, "Real Time Identification of Dynamic Events in Power Systems using PMU data, and Potential Applications – Models, Promises, and Challenges", IEEE Trans. Power Delivery – Special Issue on Innovative Research Concepts for Power Delivery Engineering, Vol. 32-1, pp. 294 – 301, Feb. 2017.