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Resilient Distribution Systems: State-of-the-Art and the Future

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Washington State University

Sponsors Include Pacific Northwest National Lab, U.S. Department of Energy, State of WA Department of Commerce

WASHINGTON STATE UNIVERSITY

World Class. Face to Face.

Smart Grid Development in U.S.

Transmission

Synchrophasors

Renewable Energy

Substation Automation

Distribution

Remote Controlled Switches

Advanced Metering Infrastructure

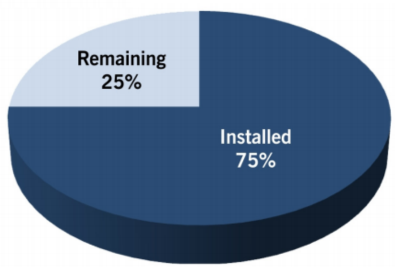
Distributed Energy Resources

Source: General Electric and CG global

SGIGs on Distribution Automation

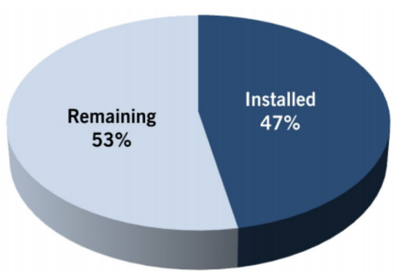
- EDS involves deployment of technologies and systems for improving distribution system operations, including: (1) outage management with devices such as automated circuit switches and reclosers, and (2) voltage/volt-ampere reactive (VAR) control with field devices such as automated capacitors, voltage regulators, and voltage sensors.

Installed SGIG Automated Switches



Automated Switches	
Number of Projects	46
Number of Automated Switches Expected at Completion	about 7,500
Number of Automated Switches Installed (as of March 31, 2012)	5,628
Expenditures (as of March 31, 2012)	$307.4 million

Installed SGIG Automated Capacitors



Automated Capacitors	
Number of Projects	43
Number of Automated Capacitors Expected at Completion	about 18,500
Number of Automated Capacitors Installed (as of March 31, 2012)	8,768
Expenditures (as of March 31, 2012)	$79.72 million

Avista Utilities, WA

Spokane and Pullman

(WSU) Smart Circuit

Project Cost: $40M

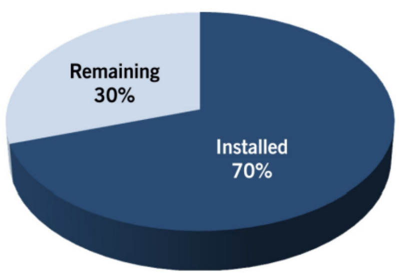
Fed Funding: $20M

Source: http://energy.gov/sites/prod/files/Smart%20Grid%20Investment%20Grant%20Program%20-%20Progress%20Report%20July%202012.pdf

SGIG Advanced Metering Infrastructure

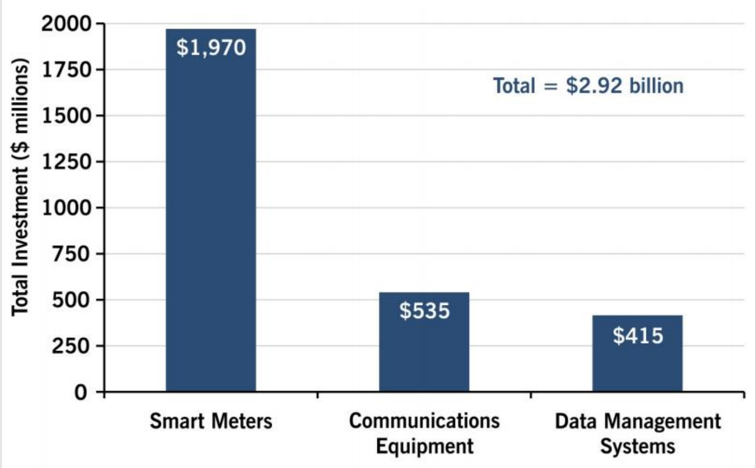
- AMI involves deployment of smart meters; communications networks to transmit data from the meters at 15, 30, or 60 minute intervals; and meter data management systems to receive, store, and process data from the meters. These projects use smart meters to collect interval load data, while some projects also use smart meters to collect data on voltages and power quality.

SGIG Smart Meter Deployment



AMI Smart Meters	
Number of Projects	65
Number of Smart Meters Expected at Completion	at least 15.5 million
Number of Smart Meters Installed (as of March 31, 2012)	10.8 million
Expenditures (as of March 31, 2012)	$1,970 million

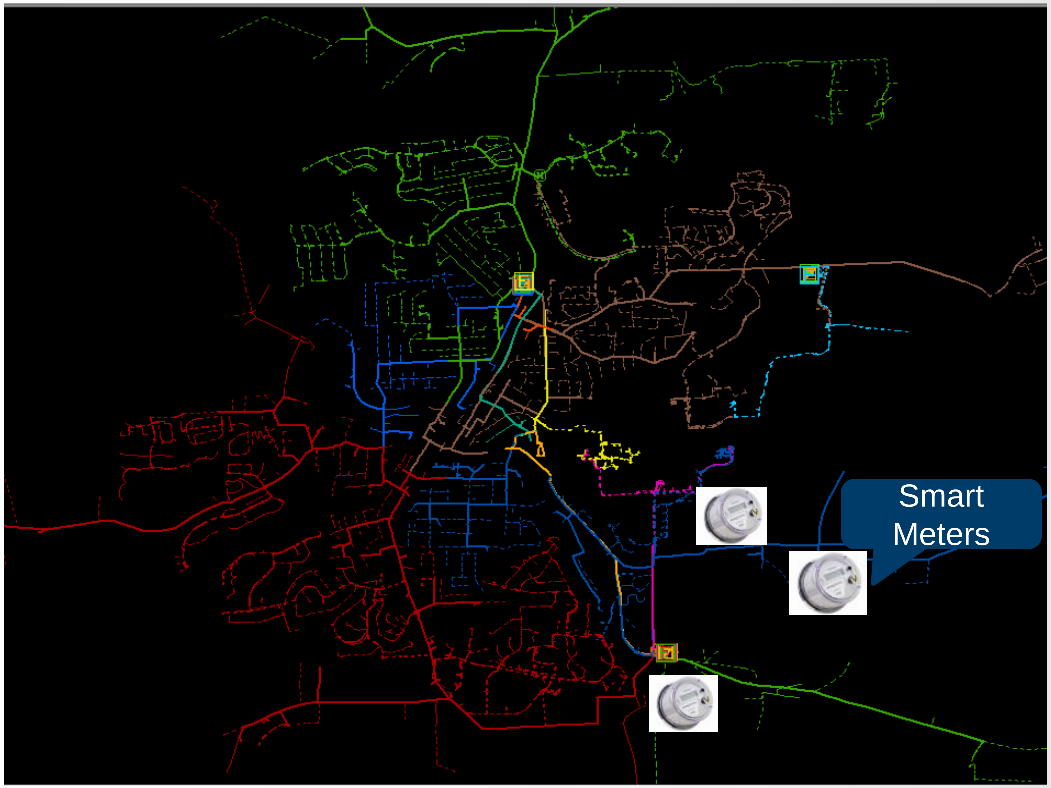
SGIG AMI Project Expenditures on Technologies and Systems



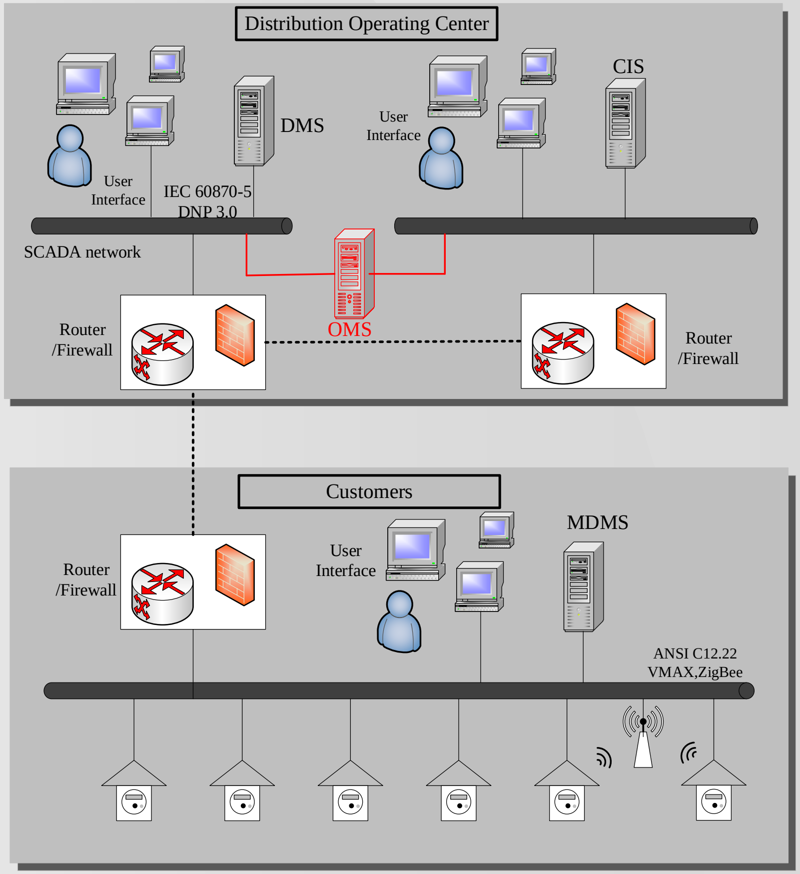
Source: http://energy.gov/sites/prod/files/Smart%20Grid%20Investment%20Grant%20Program%20-%20Progress%20Report%20July%202012.pdf

Outage Management Using Smart Meters

- Up to several hours to collect trouble calls for outage management
- Smart outage management using notifications from smart meters



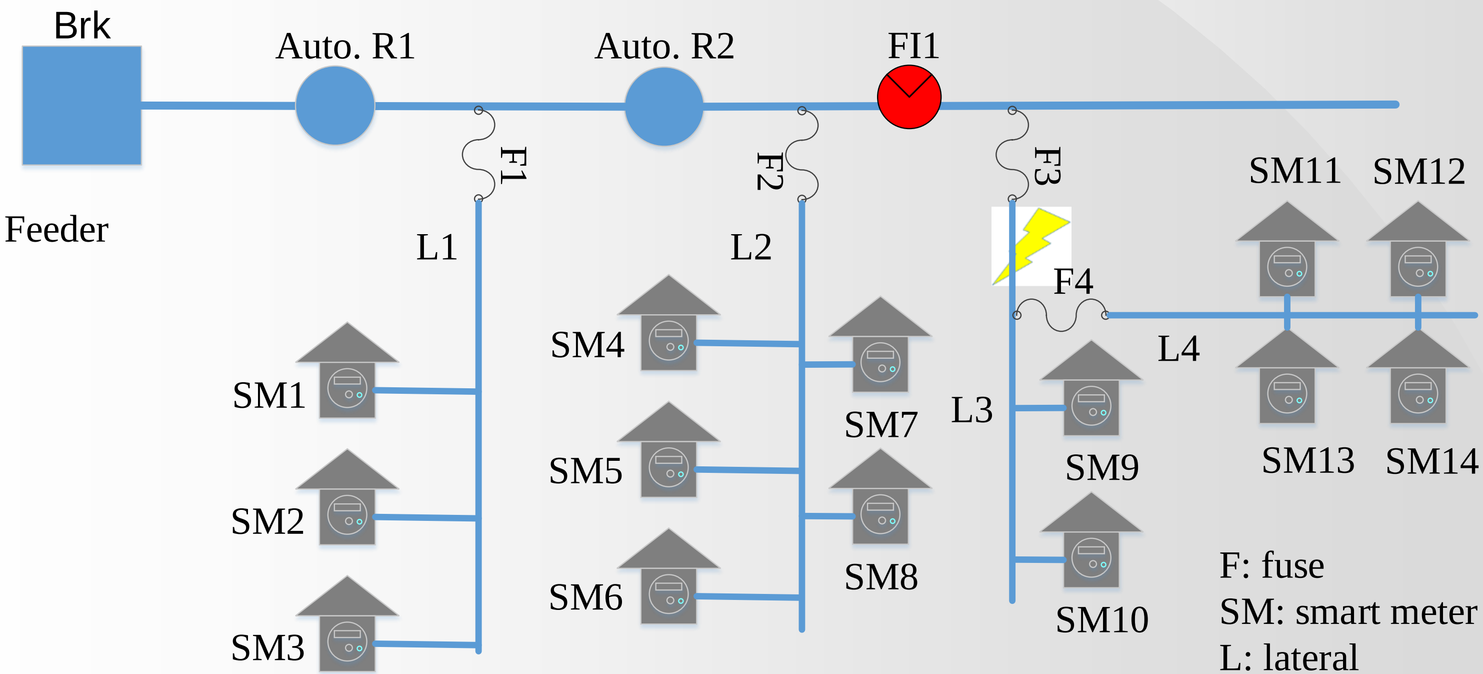
Pullman Smart Grid



Smart Outage Management System (OMS)

Outage Management Incorporating Smart Meters

- One-line diagram of a distribution system:

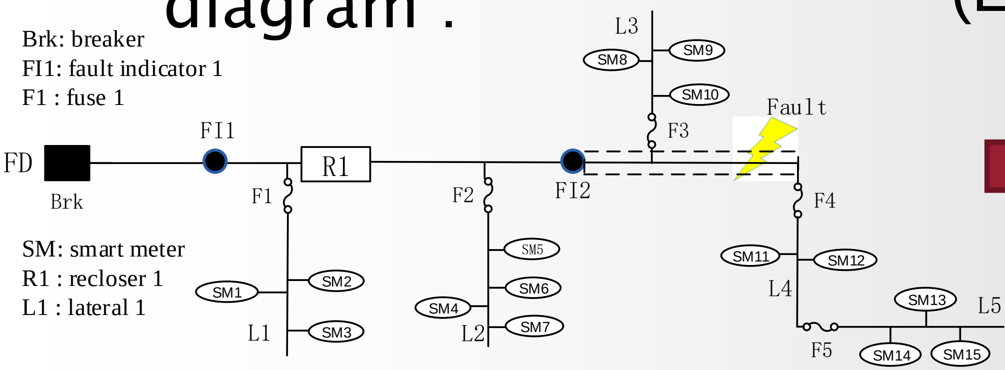


- Evidence:
  - Overcurrent flags from FI1, R2, R1;
  - Outage reports from smart meters downstream of Fuse3.

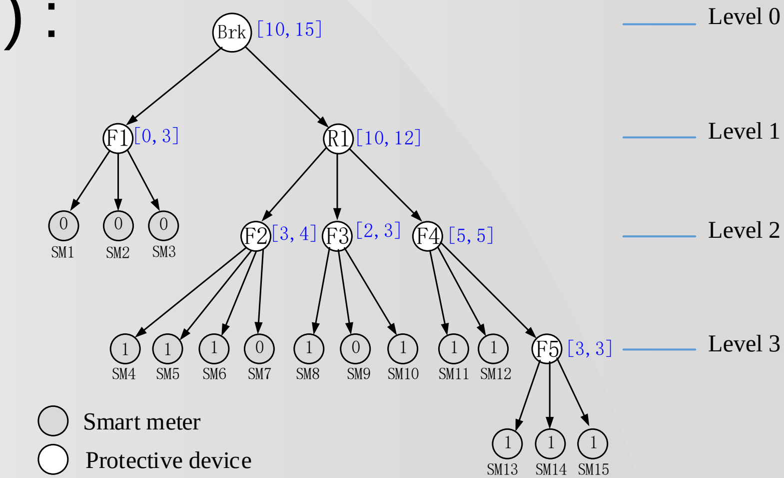
- OMS:
  - Determine the actuated protective device
  - Determine the faulted line section

Outage Management System (OMS)

- One-line diagram :



- Extended Protection Tree (EPT) :



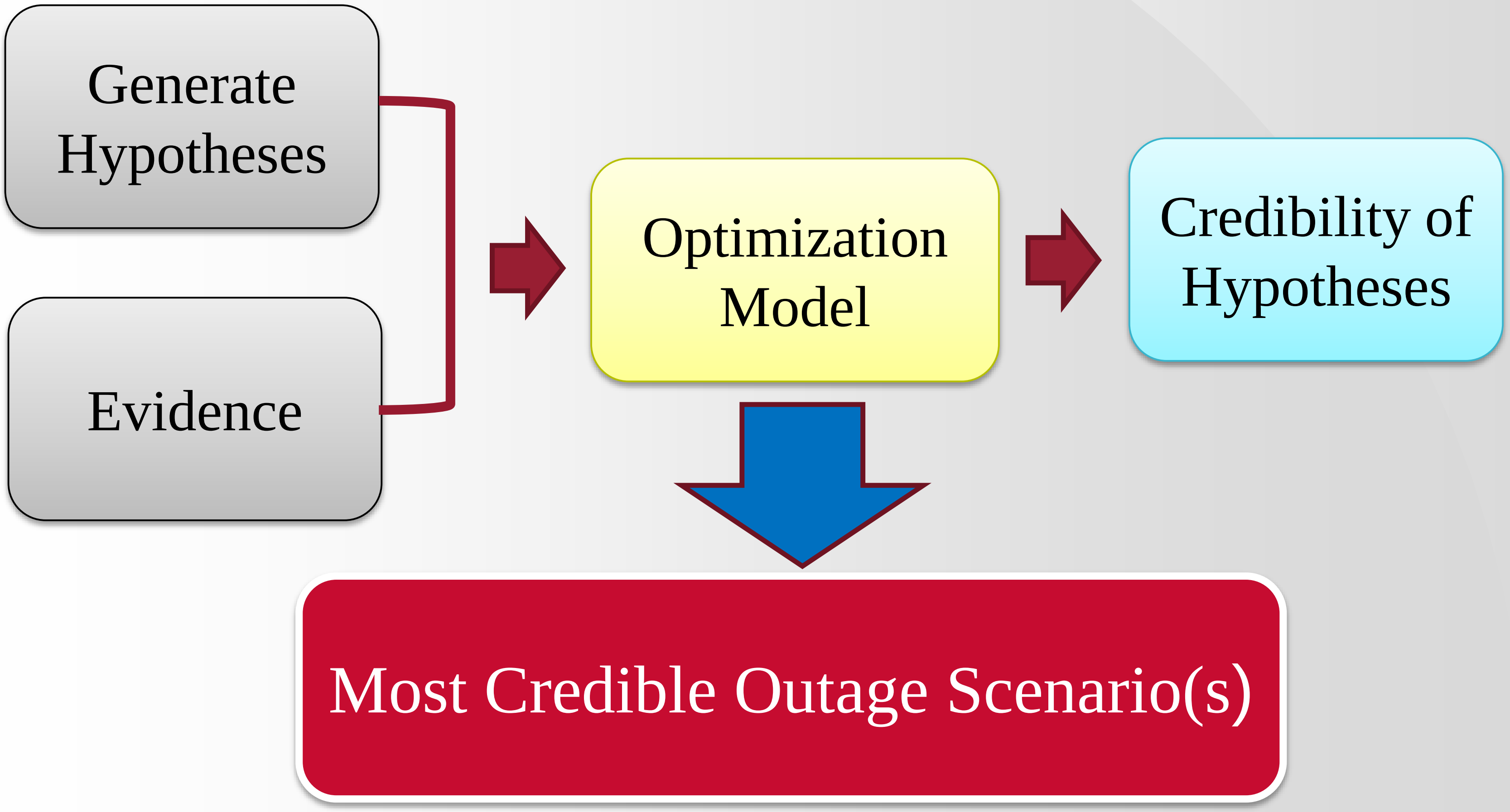
➢ A flag from FI1 (FI2 fails to send a flag);

➢ Notifications from smart meters downstream of R1.

➢ Determine the actuated protective device;

➢ Determine the faulted line section.

Multiple-Hypothesis Incorporating Smart Meters



Y. Jiang, C. C. Liu, M. Diedesch, E. Lee, A. Srivastava, “Outage Management of Distribution Systems Incorporating Information from Smart Meters,” IEEE Trans. Power Systems.

Optimization Model for OMS

Objective

Maximize *the credibility of the outage scenario*

Subject to following constraints:

Logical constraints:

i) fault indicators sending flags should be upstream of faulted line section

ii) actuated protective device should be upstream of the faulted line section

Constraints associated with hypotheses:

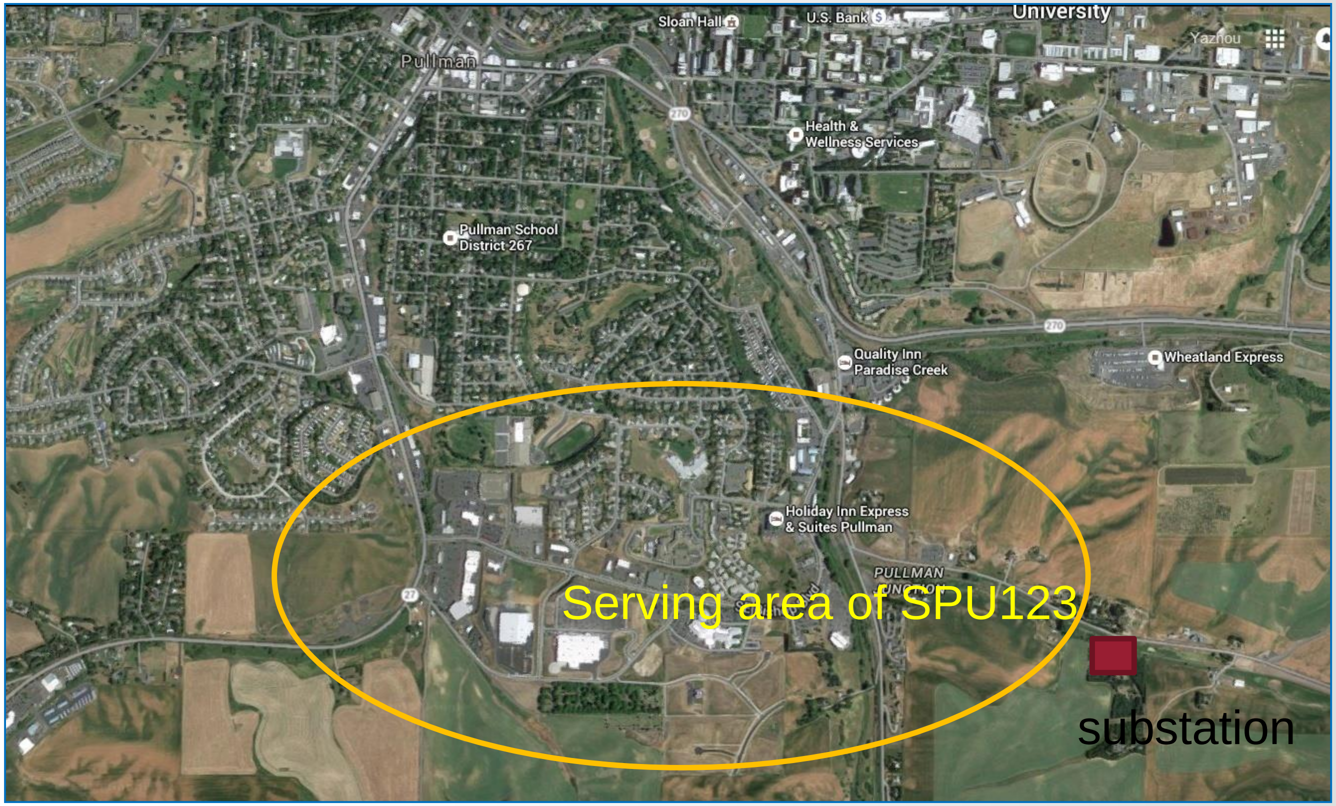
iii) number and locations of multiple faults

iv) number and locations of fault indicator failures

v) number of protection miscoordination pairs

Test System

- Pullman System Feeder SPU123:



- ➢1320 customers
- ➢ 579 line sections
- ➢ 33 fuses
- ➢ 3 automatic reclosers
- ➢1 automated switch

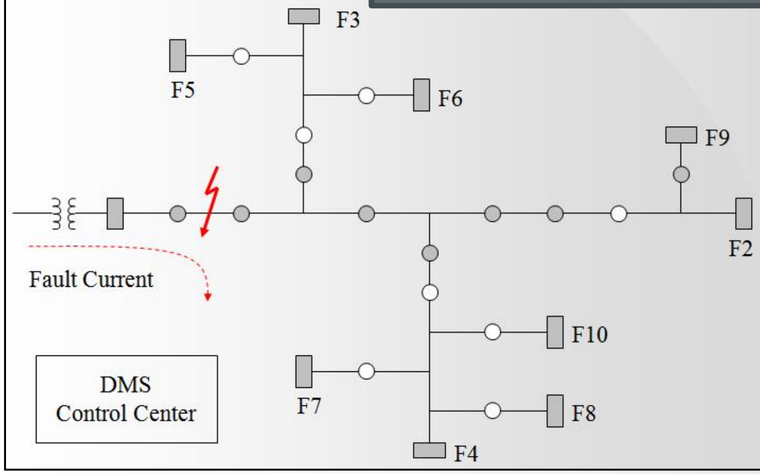
Multiple-Hypothesis Results

Hypo.	Actuated device(s)	Faulted section(s)	$N_{SM-Correct}$	$N_{SM-Unreport}$	$N_{SM-Incorrect}$	Abnormality of fault indicator failures and protection miscoord.	E_1	E_2	Cred.
1	Fuse20	Link4	50	37	0	ϕ	0.574	1	0.787
2	Fuse20	Link6/5	50	37	0	Fuse14/16-Fuse20 miscoord.	0.574	1	0.787
3	Auto.R1	Link2	50	897	0	R2 should not send a flag	0.053	0.75	0.401
4	Auto.R2	Link10	50	584	0	R3-R2 miscoord. and R3 should send a flag	0.079	0.75	0.414
5	Fuse20 and Fuse21	Link4 and Link11	50	58	0	ϕ	0.463	1	0.732
6	Fuse20 and Fuse21	Link6/5 and Link11	50	58	0	Fuse14/16-Fuse20 miscoord.	0.463	1	0.732
7	Fuse20 and Fuse29	Link4 and Link9	50	54	0	R3 should send a flag	0.481	0.75	0.615
8	Fuse20 and Fuse29	Link6/5 and Link9	50	54	0	Fuse14/16-Fuse20 miscoord. and R3 should send a flag	0.481	0.75	0.615

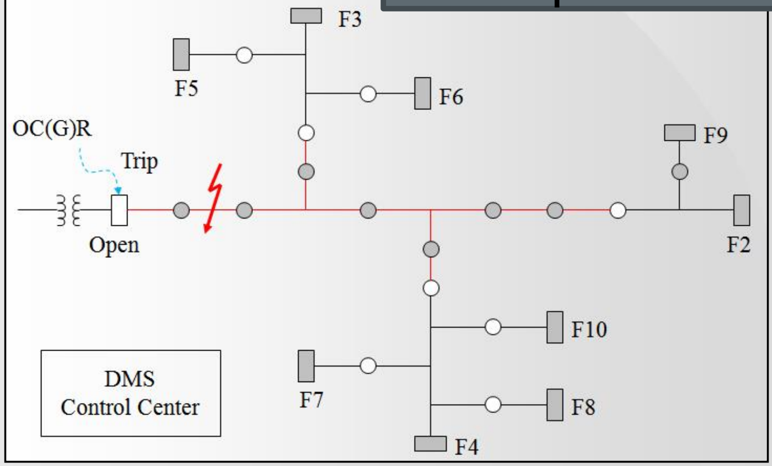
- hypotheses 1 and 2 are the most credible outage scenarios;
- scenario of fuse20 actuated is most credible;
- if Fuse14/16 and Fuse20 are miscoordinated, the faulted line section is Link6/5. Otherwise, Link4 is faulted.

Service Restoration with DA

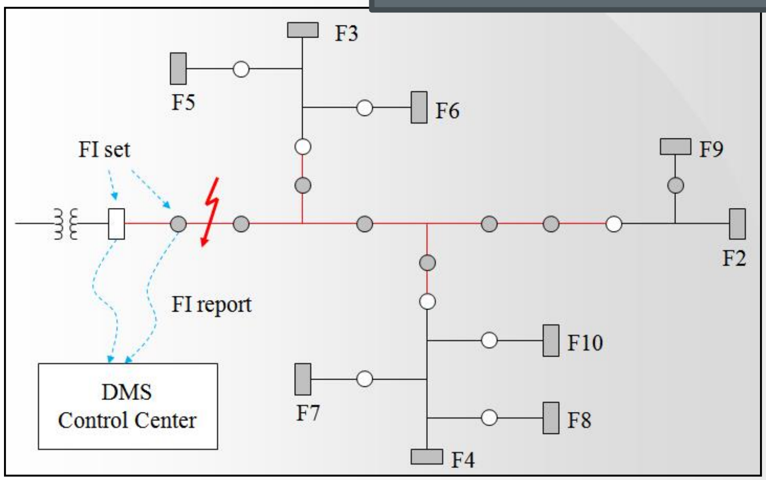
1. Fault occurs



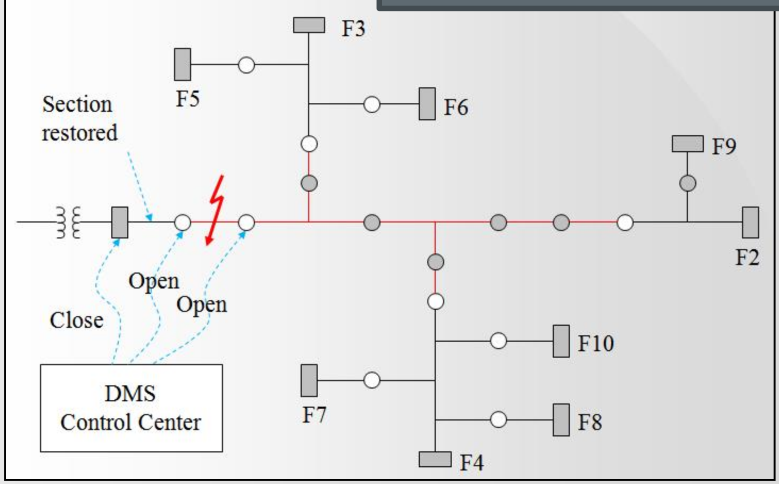
2. Open CB



3. Find fault



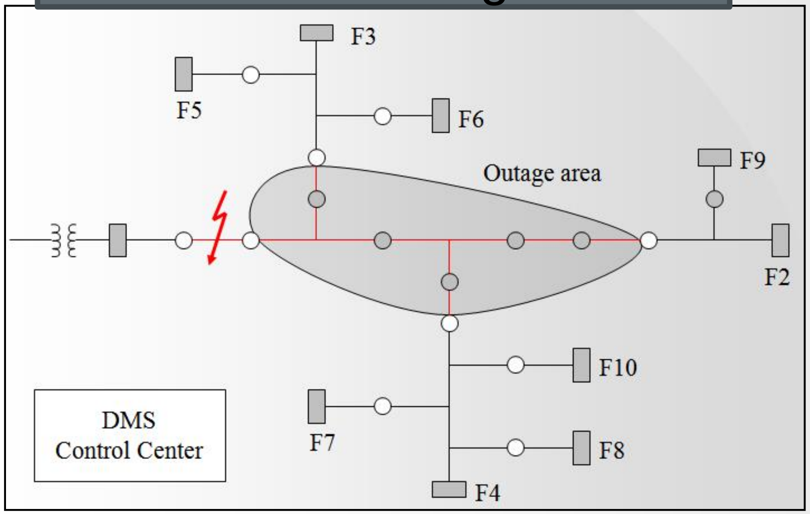
4. Isolation



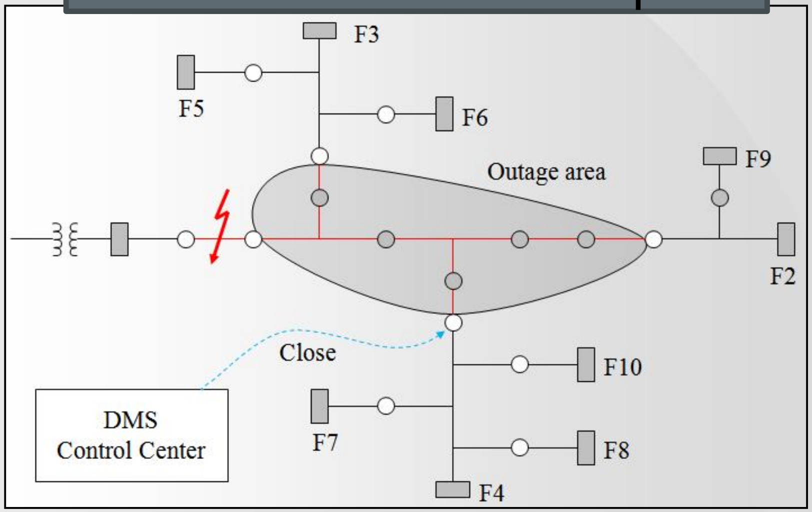
*KEPCO: Intelligent DA System

Service Restoration with DA

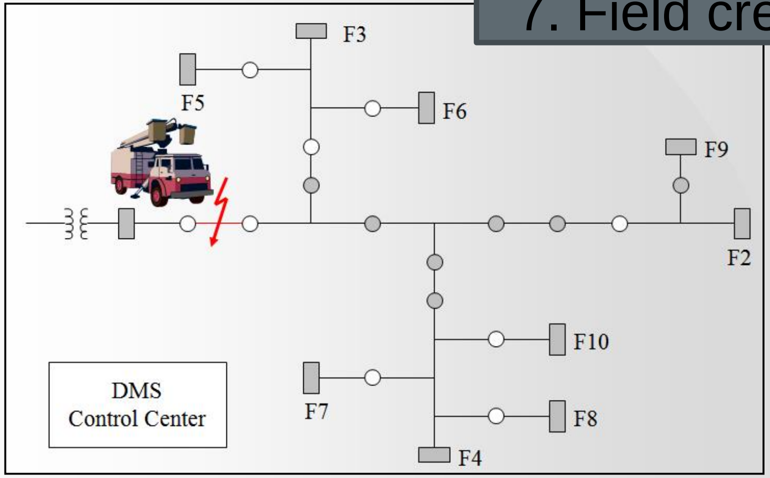
5. Transfer outage area



6. Execute restoration plan



7. Field crew



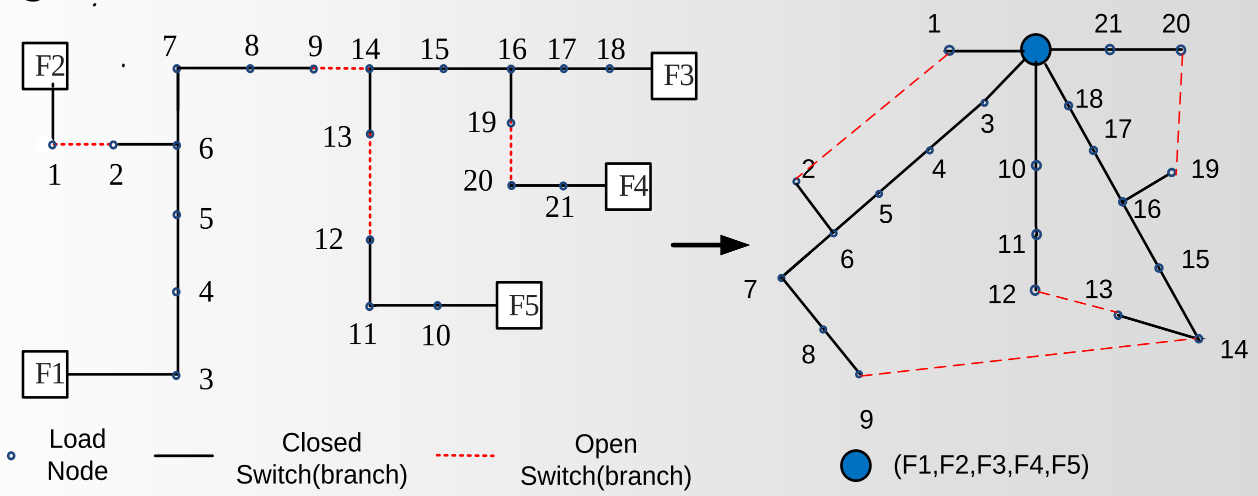
C.C. Liu, S.J. Lee, S.S. Venkata, "An Expert System Operational Aid for Restoration and Loss Reduction of Distribution Systems" *IEEE Trans. Power Systems*, May 1988.

S. J. Lee, S. I. Lim, B. S. Ann, "Service Restoration of Primary Distribution Systems Based on Fuzzy Evaluation of Multi-Criteria," *IEEE Trans. Power Systems*, Aug. 1998.

*KEPCO: Intelligent DA System

Distribution Restoration: “Spanning Tree” Method

- Radial structure of the distribution network can be represented by a spanning tree (a circuit graph).
- Restoration can be formulated as a problem of finding a desired spanning tree structure and a sequence of operations that change one spanning tree into another.

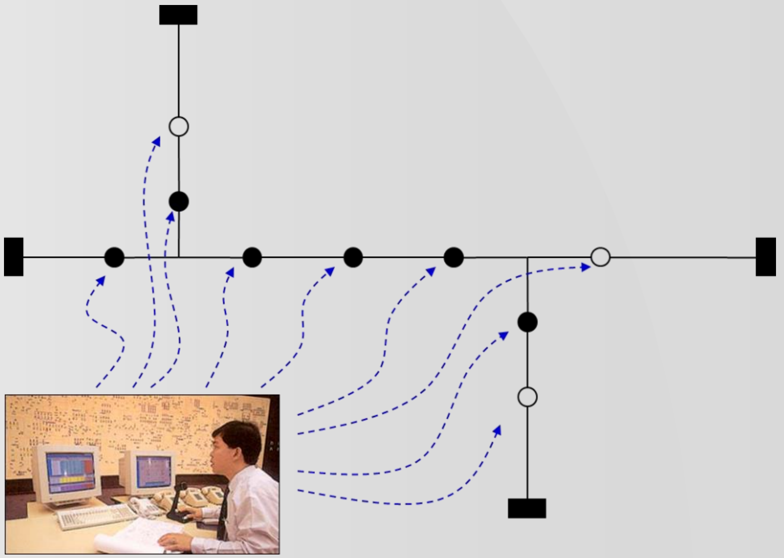


Spanning Tree software has been integrated into PNNL GridLAB-D and available on GridLAB-D web site.

J. Li, X. Y. Ma, C. C. Liu, K. Schneider, “Distribution System Restoration with Microgrid Using Spanning Tree Search, “ IEEE Trans. Power Systems, Nov. 2014, pp. 3021-3029.

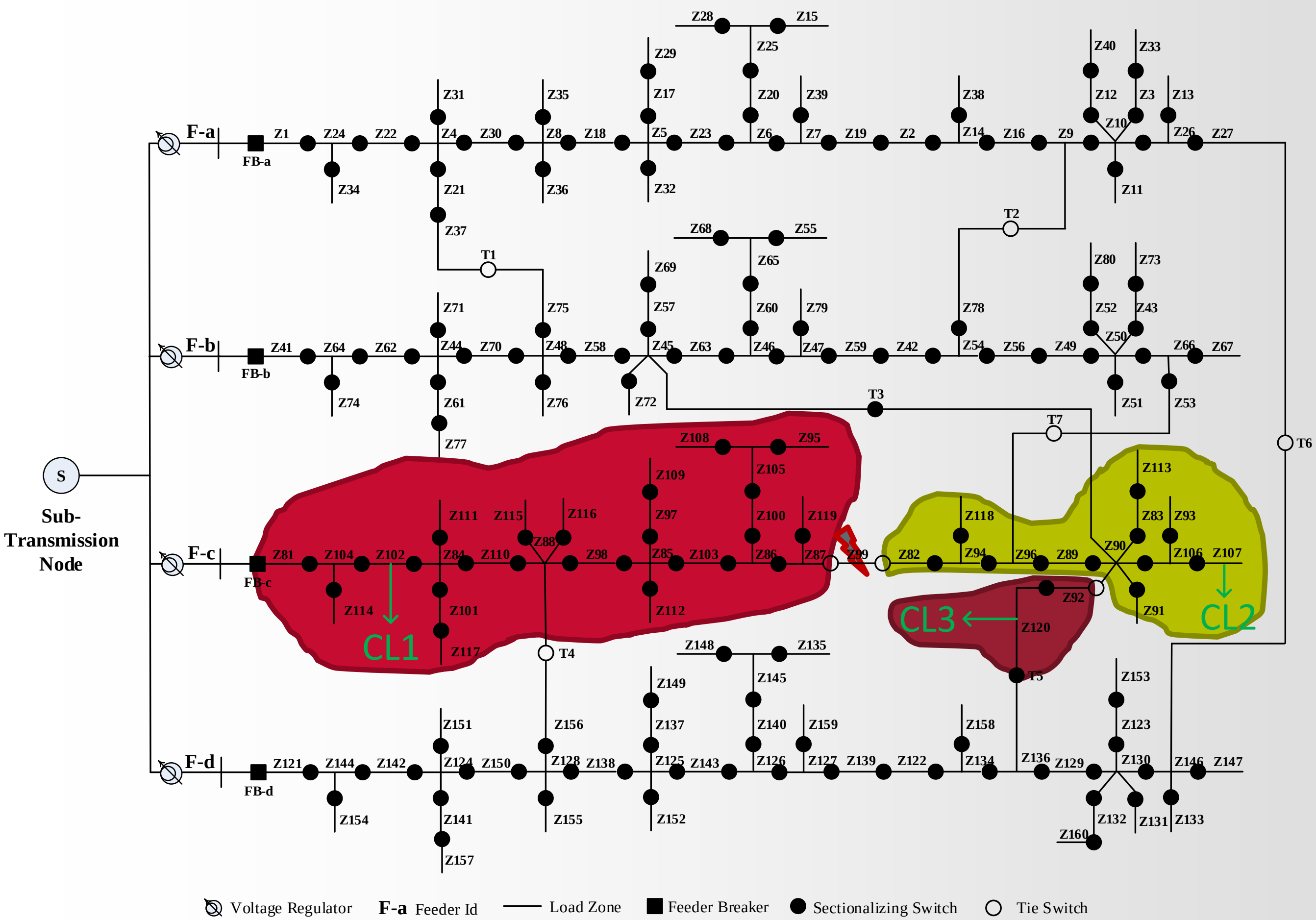
Enhance Restoration Capability by Adding Remote Control Functions

- A remote-controlled switch (RCS) can be operated by a distribution system operator. A manual switch is operated by the field crew.
- Installing RCSs enhances restoration capability of a distribution system.
- Microsoft campus, Redmond, WA



Restoration Scheme Without RCSs

- A fault occurs at zone Z99
- Mean time to operate a manual switch is assumed to be 60 minutes



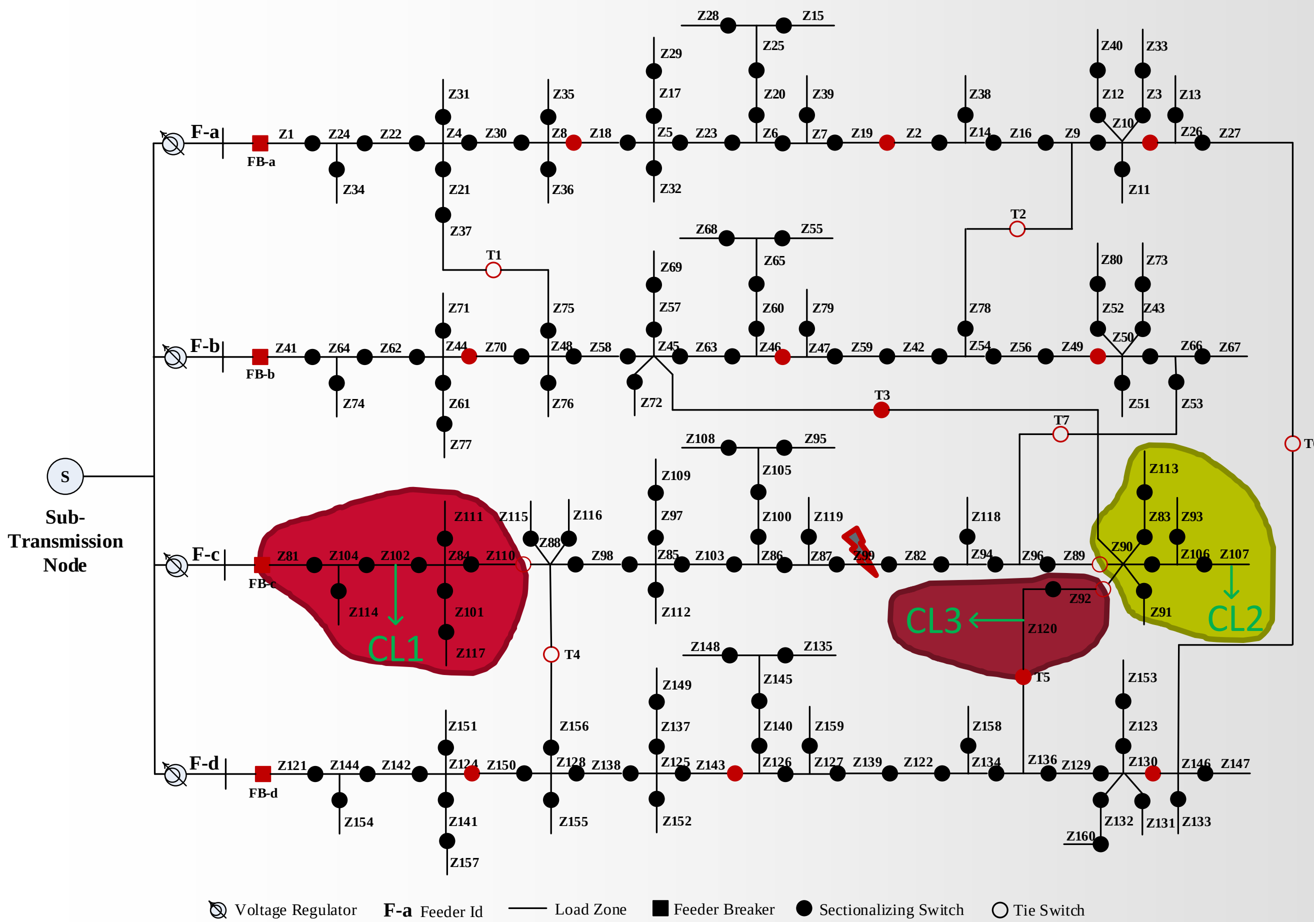
Recovery Process

- Open “87-99” and “99-82” to isolate Z99;
- Reclose “FB-c” to restore loads upstream Z99;
- Open “90-92” and close “T3” and “T5” to restore loads downstream Z99 in two groups.

Critical Load	Outage Time (min)
CL1	180
CL2	300
CL3	360

Restoration Scheme With RCSs

- A fault occurs at zone Z99
- Mean time to operate a manual switch is assumed to be 60 minutes
- Mean time to operate a RCS is assumed to be 1 minute



Recovery Process

- Open “110-88” and “89-90” to separate critical loads from faulted zone;
- Reclose “FB-c” to restore CL1;
- Open “90-92” and close “T3” and “T5” to restore CL2 and CL3;
- Open “87-99” and “99-82” and close “110-88” and “89-90” to restore other loads.

Critical Load	Outage Time (min)
CL1	3
CL2	5
CL3	6

Problem Transformation

- Since load zones in a Restorable Load Group (RLG) can be restored by the corresponding Basic Switch Group (BSG) or Extended Switch Group (ESG) in any single fault scenario, the RLG is ***covered*** by the corresponding BSG/ESG.
- With all RLG-BSG/ESG pairs, we can formulate RCS Placement as a ***<u>Weighted Set Cover</u>*** Problem.
  - Objective: cover all load zones that can be covered* with minimum number of switches.

$$\min \left| \bigcup_{j:z_j=1} \boldsymbol{G}_{S,j} \right|$$

Subject to

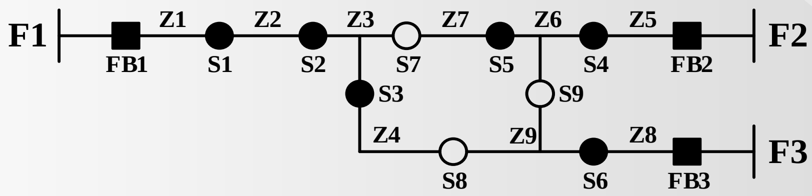
$$z_j \in \{0,1\}, j = 1,2, \dots, m$$

$$\sum_{j=1}^{m} a_{ij} z_j \geq 1, i = 1,2, \dots, n$$

$$\boldsymbol{x} = \bigcup_{j \in \boldsymbol{C}} \boldsymbol{G}_{s,j}.$$

* Some load zon

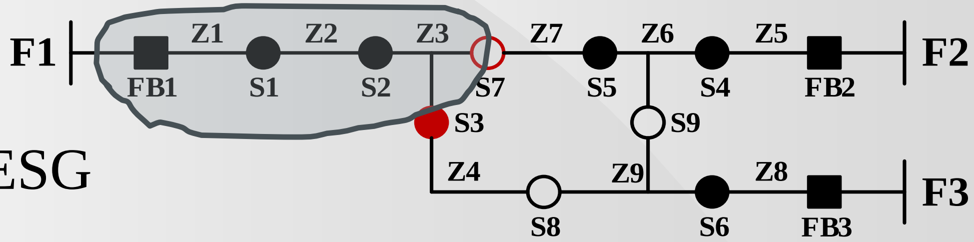
Step 1: Search for RLG-BSG/ESG Pairs



Index i	RLG $G_{l,i}$	BSG or ESG $G_{s,i}$
1	{Z3}	{S7, S2, S3}
2	{Z3}	{S7, S2}
3	{Z2, Z3}	{S7, S1, S3}
4	{Z1, Z2, Z3}	{S7, S3}
5	{Z7}	{S8, S3, S7, S5}
6	{Z6, Z7}	{S8, S3, S7, S4}
7	{Z5, Z6, Z7}	{S8, S3, S7}
8	{Z4}	{S8, S3}
9	{Z9}	{S8, S6}
10	{Z9}	{S9, S6}
11	{Z6}	{S9, S4, S5}
12	{Z6}	{S9, S4}
13	{Z5, Z6}	{S9, S5}

* FBs are assumed to be remote-controlled.

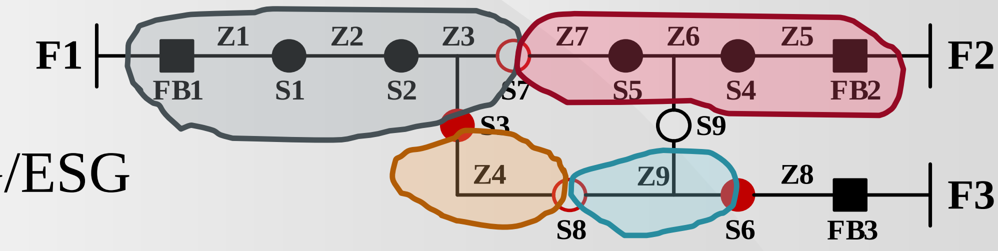
Step 3: Greedy Search



- **Iteration 1**: #4 RLG-BSG/ESG pair is selected.

Index i	RLG $G_{l,i}$	BSG or ESG $G_{s,i}$	N_s/N_l
1	{Z3}	{S7, S2, S3}	3
2	{Z3}	{S7, S2}	2
3	{Z2, Z3}	{S7, S1, S3}	1.5
4	**{Z1, Z2, Z3}**	**{S7, S3}**	**2/3**
5	{Z7}	{S8, S3, S7, S5}	4
6	{Z6, Z7}	{S8, S3, S7, S4}	2
7	{Z5, Z6, Z7}	{S8, S3, S7}	1
8	{Z4}	{S8, S3}	2
9	{Z9}	{S8, S6}	2
10	{Z9}	{S9, S6}	2
11	{Z6}	{S9, S4, S5}	3
12	{Z6}	{S9, S4}	2
13	{Z5, Z6}	{S9, S5}	1

Step 3: Greedy Search (Cont’d)



- **Iteration 4**: #9 RLG-BSG/ESG pair is selected.

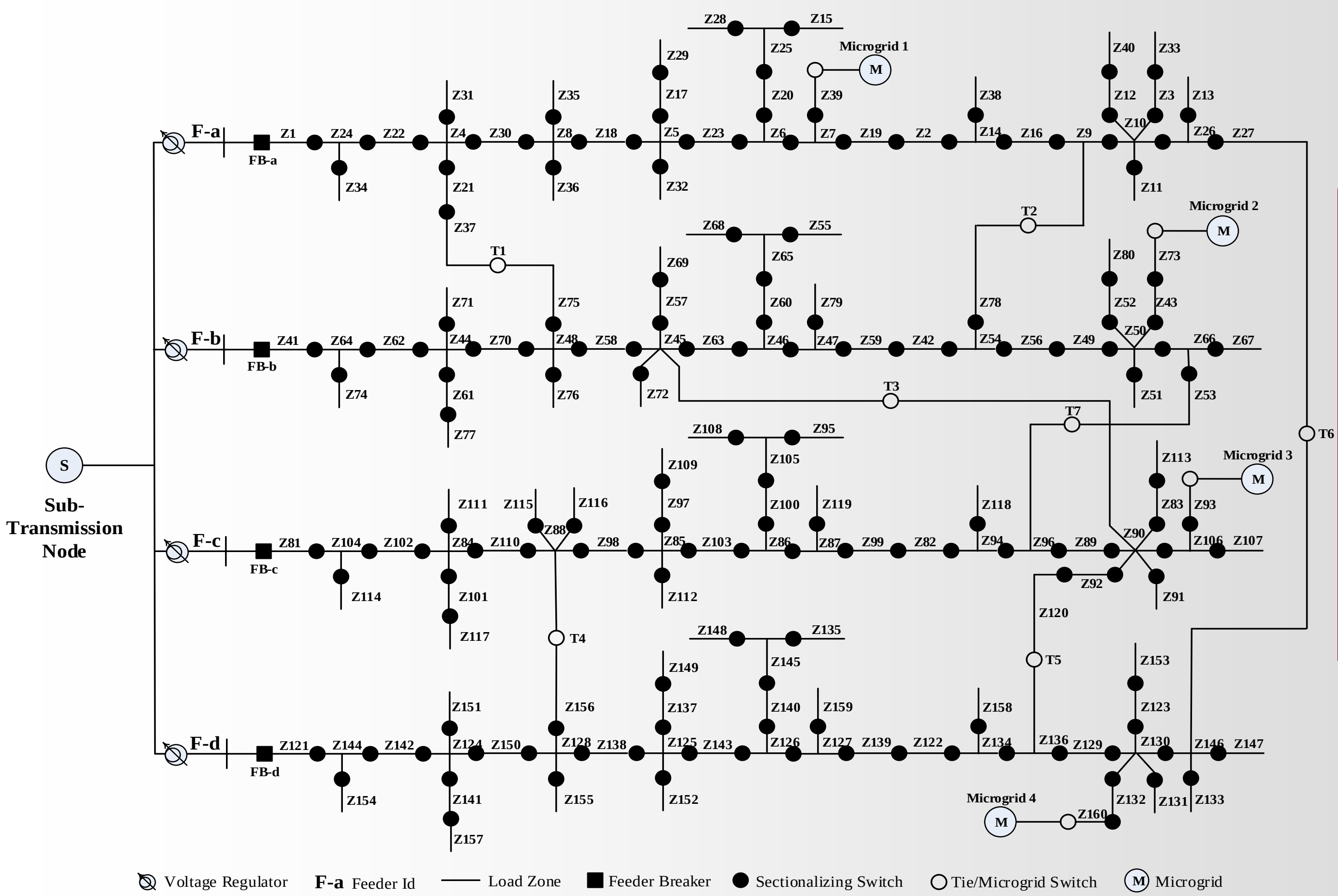
Index i	RLG $G_{l,i}$	BSG or ESG $G_{s,i}$	N_s/N_l
1	∅	{S2}	∞
2	∅	{S2}	∞
3	∅	{S1}	∞
4	**{Z1, Z2, Z3}**	**{S7, S3}**	
5	∅	{S5}	∞
6	∅	{S4}	∞
7	**{Z5, Z6, Z7}**	**{S8}**	
8	**{Z4}**	∅	**0**
9	**{Z9}**	**{S6}**	**1**
10	{Z9}	{S9, S6}	2
11	∅	{S9, S4, S5}	∞
12	∅	{S9, S4}	∞
13	∅	{S9, S5}	∞

Enhancement of Automation on *Microsoft Campus in Redmond*

Project for Puget Sound Energy (PSE) and Microsoft:

"Microsoft and PSE have jointly used the results of the WSU study in conjunction with both our company's knowledge of the Redmond campus's distribution system to develop a plan for installing up to six additional SCADA switches on the Redmond campus."

PNNL Test System



Remote-Controlled Switches (RCSs)

- 4 feeder breakers
- 8 normally closed sectionalizing switches
- 5 normally closed tie switches
- 4 microgrid switches

Improvement in Reliability

- SAIDI, SAIFI and Outage Cost are calculated. *

Index	Without RCSs	With RCSs	Improvement
SAIDI (minute/year)	181.72	44.17	75.70%
SAIFI (/year)	0.7800	0.6548	16.05%
Outage Cost (k$/year)	93.024	18.283	80.35%

* Assume that the permanent failure rate for each zone is 0.02, the mean time to operate a manual/remote-controlled switch is 90/1 minutes, and the cost for outage load is $3.3 per customer per hour, respectively.

Damages to Distribution Grids by Superstorm Sandy

Downed power lines and other debris litter the streets of Seaside Heights, N.J., on 31 October 2012, two days after Superstorm Sandy made landfall in the US.*

The storm surge that accompanied Superstorm Sandy sent water rushing through the streets near a substation in Brooklyn, N.Y. Restoring a flooded substation takes much longer than restoring a downed power line because of the large amounts of water, rust, and mud left trapped in the structure.*

* Source: Nicholas C. Abi-Samra, “One Year Later: Superstorm Sandy Underscores Need for a Resilient Grid”, IEEE Spectrum, http://spectrum.ieee.org/energy/the-smarter-grid/one-year-later-superstorm-sandy-underscores-need-for-a-resilient-grid

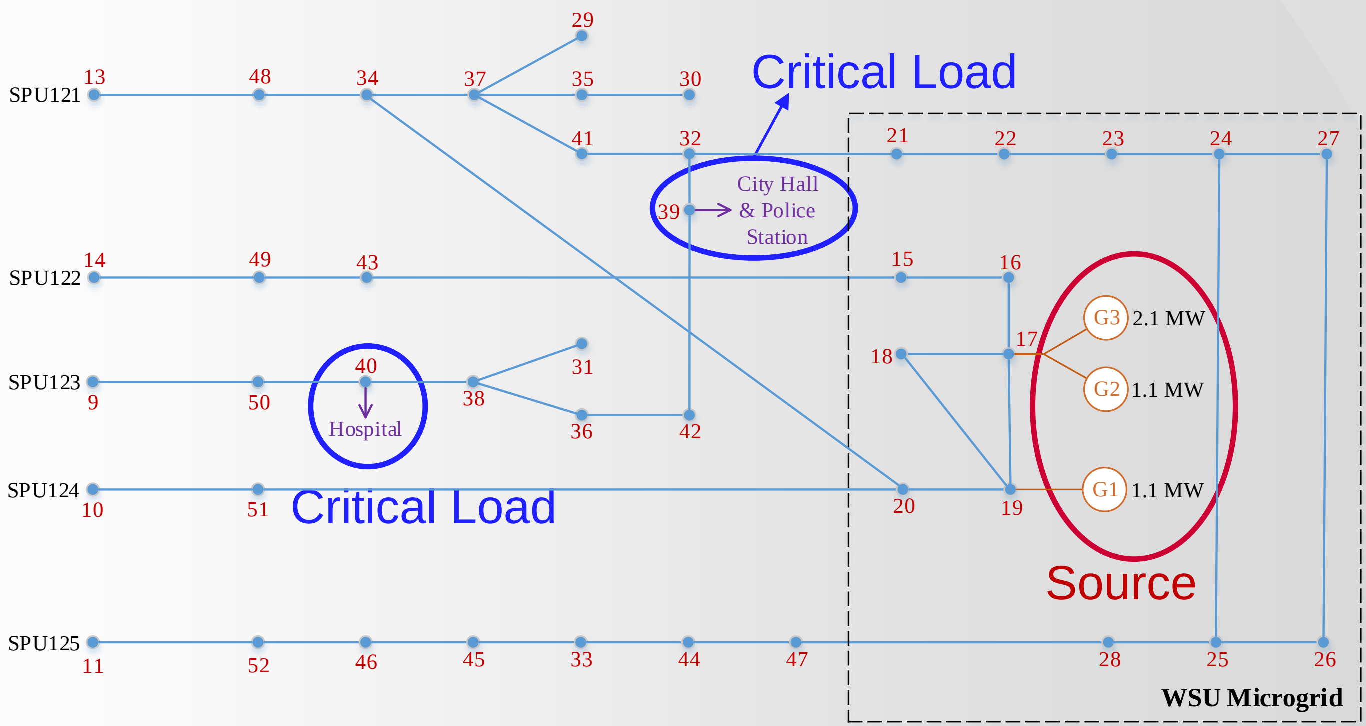
Typical Outages and Catastrophic Outages Due to Extreme Events

Typical Outages	Catastrophic Outages
• **Single fault**: In most cases, there is only one faulted component.	• **Multiple faults**: Multiple electrical facilities are damaged.
• **Small amount of load and a small number of customers are involved.**	• **Large amount of load and a large number of customers are out of services.**
• **Power is available**: Most power sources are working and stay connected.	• **Lack of power**: Power sources can not access the load or are out of service.
• **T&D network remains intact**: Outage loads are easily connected to sources.	• **T&D network damaged**: Overhead lines, transformers, substations are damaged.
• **Easy to repair and restore**	• **Difficult to repair and restore**

C. C. Liu, "Distribution Systems: Reliable But Not Resilient," *In My View*, IEEE Power and Energy Mag., May/June 2015.

Microgrid Supports Fast Recovery of Distribution Systems

- Spanning Tree Search algorithm is applied to WSU-Pullman system to find restoration paths from DERs to critical loads outside campus microgrid.



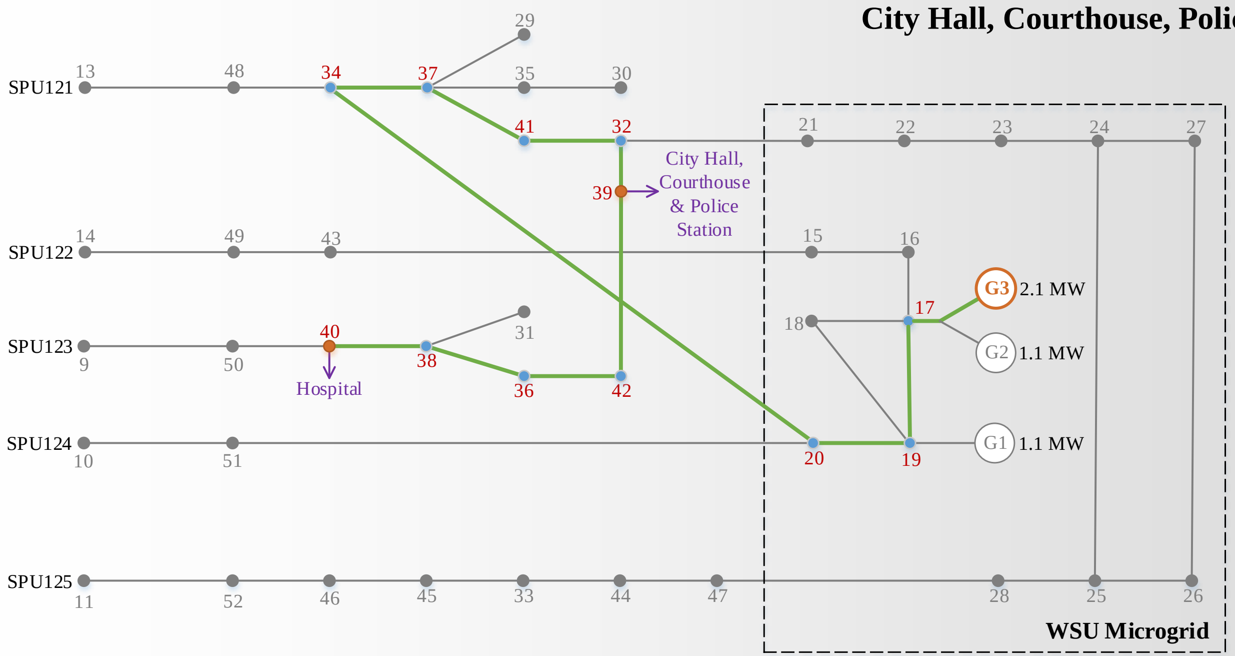
Microgrid Supports Fast Recovery of Distribution Systems

- Restoration Path:

G3 → 17 → 19 → 20 → 34 → 37 → 41 → 32 → 39 → 42 → 36 → 38 → 40

City Hall, Courthouse, Police Station

Hospital



G3, a diesel generator, is used to pick up critical loads, i.e., City Hall, Courthouse, Police Station and Hospital.

Microgrid Supports Fast Recovery of Distribution Systems

- Validation by GridLAB-D Power Flow

G3 → 17 → 19 → 20 → 34 → 37 → 41 → 32 → 39 → 42 → 36 → 38 → 40

City Hall, Courthouse, Police Station (39)

Hospital (40)

Output of G3 (Capability of G3 is 2.1MW)

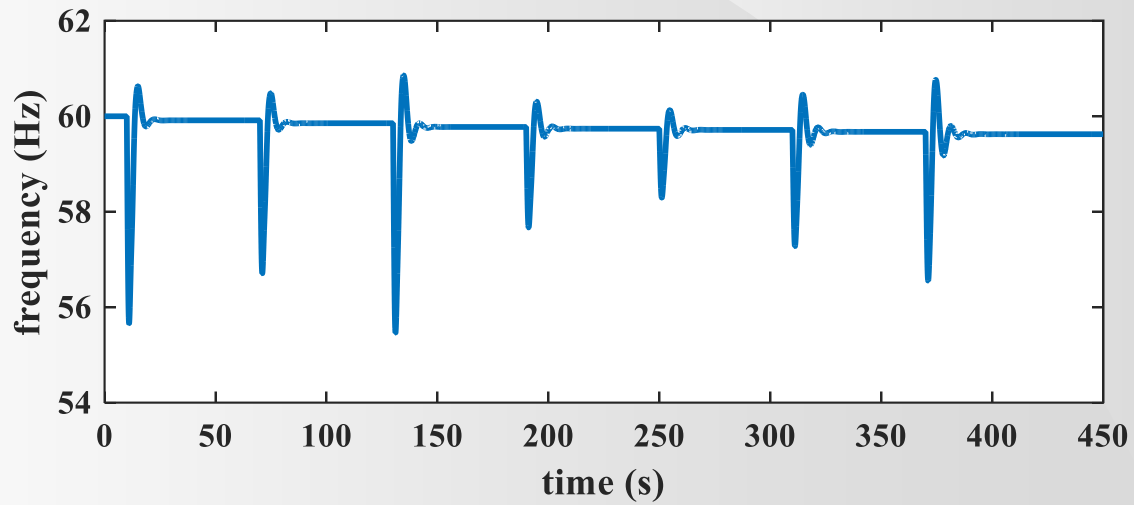
DER Name	Active Power(W)	Reactive Power(Var)	Apparent Power(VA)
G3	1.128e+06	6.5095e+05	1.3024e+06

Load Voltage (Nominal voltage is 7967.43V)

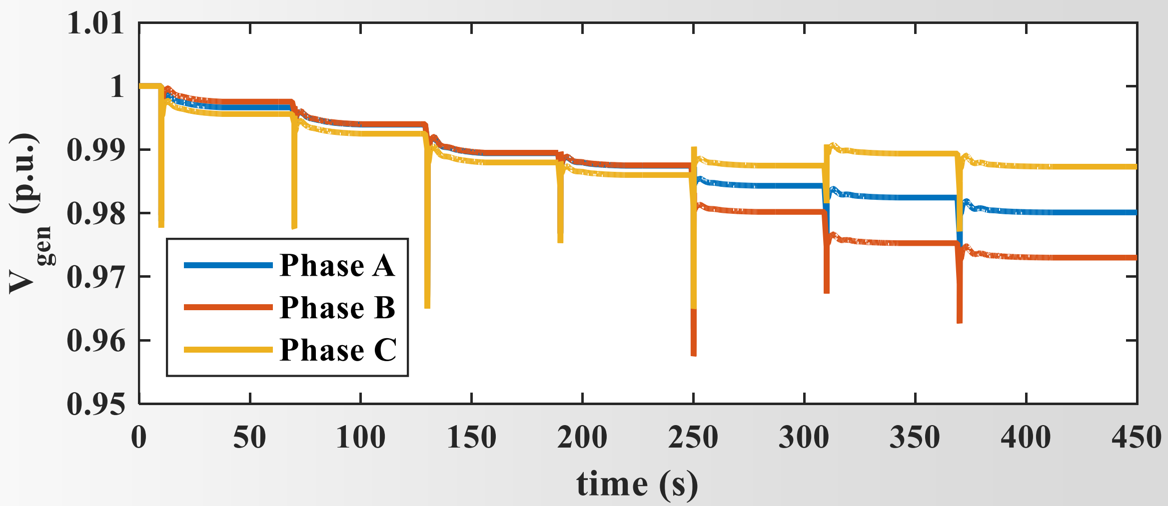
Section #	Voltage(V)	Voltage(p.u.)
17	7962.6	0.9994
19	7951.3	0.9980
20	7940.8	0.9967
34	7935.3	0.9960
37	7929.1	0.9952
41	7926.1	0.9948
32	7923.9	0.9945
39(C)	7916.6	0.9936
42	7915.9	0.9935
36	7914.6	0.9934
38	7914.0	0.9933
40(H)	7911.2	0.9929

Validation by GridLAB-D Dynamic Simulation

System Frequency



Generator Terminal Voltage



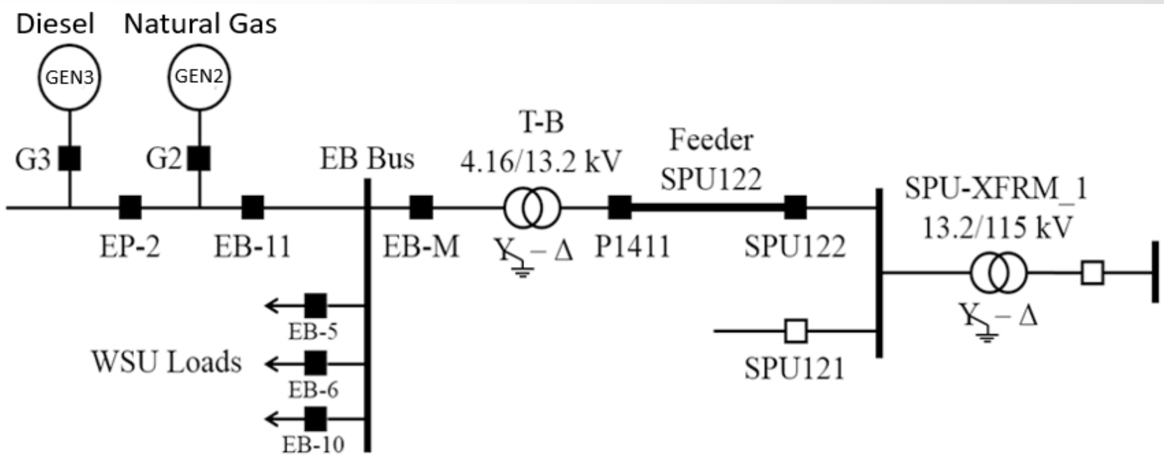
Y. Xu, C. C. Liu, K. P. Schneider, F. K. Tuffner, D. Ton, "Microgrids for Service Restoration to Critical Load in a Resilient Distribution System," Accepted for IEEE Trans. Smart Grid.

Actual Field Test at WSU

- Open breaker at 115kV side of transformer SPU-XFRM_1
- Open breakers SPU122, P1411, EB-M, and EB-11

- Start GEN3
- Close EB-11
- Restore loads at EB bus:
  - Close EB-10
  - Close EB-5
  - Close EB-6
- Close EB-M to energize transformer (last for 4s)

- Return test system to normal state



Conclusion:

- The field test demonstrates the feasibility of using microgrids as a local/community resource
  - Load restoration
  - Transformer energization
- Since we did not energize the 115kV transformer at the South Pullman Substation, we are not able to demonstrate the potential to use microgrids as a blackstart resource.

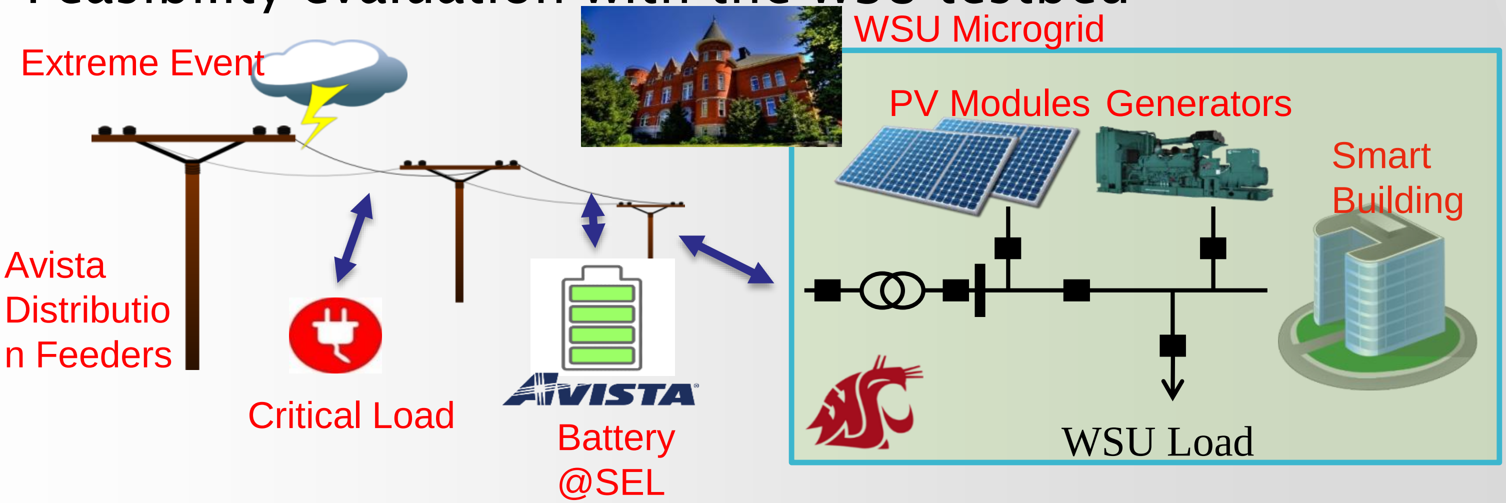
WSU Smart City Testbed

72 kW PV System (State of Washington and U.S. Department of Energy)

WSU Research and Technology Park, Pullman

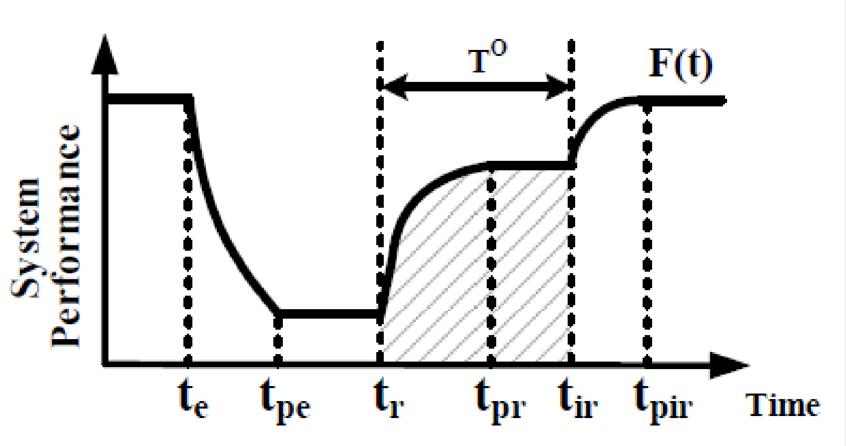
Resiliency of Distribution Systems with PVs, Batteries and Smart Buildings

- Define resiliency for an isolated distribution system with PVs, batteries, smart buildings, and WSU microgrid generators
- Optimal utilization of PVs, batteries, and WSU microgrid generators to serve critical load during system restoration
- Explore the role of smart buildings in resiliency enhancement
- Feasibility evaluation with the WSU testbed



Resilience: Definition and Metric

- PPD21 Definition: "..ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.." *
- Metric: System performance and resilience



***Resilience* refers to total amount of ENERGY served to critical load during the preset time period**

- For distribution power systems, *system performance* $F(t)$ can be specified as the total amount of power serve to critical load at time t

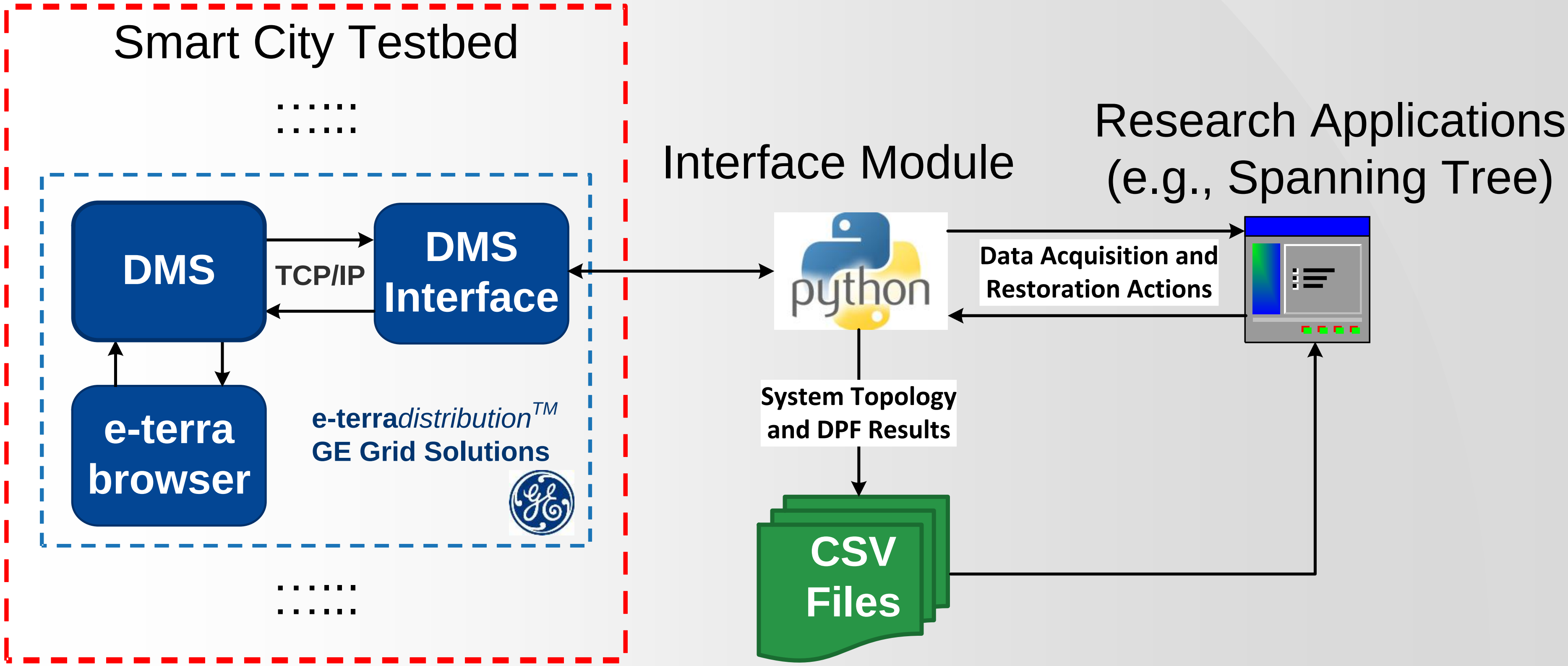
* Office of the Press Secretary of the White House, Presidential Policy Directive 21 – Critical Infrastructure Security and Resilience [Online]. Available: http://www.whitehouse.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil

Objective of Critical Load Restoration

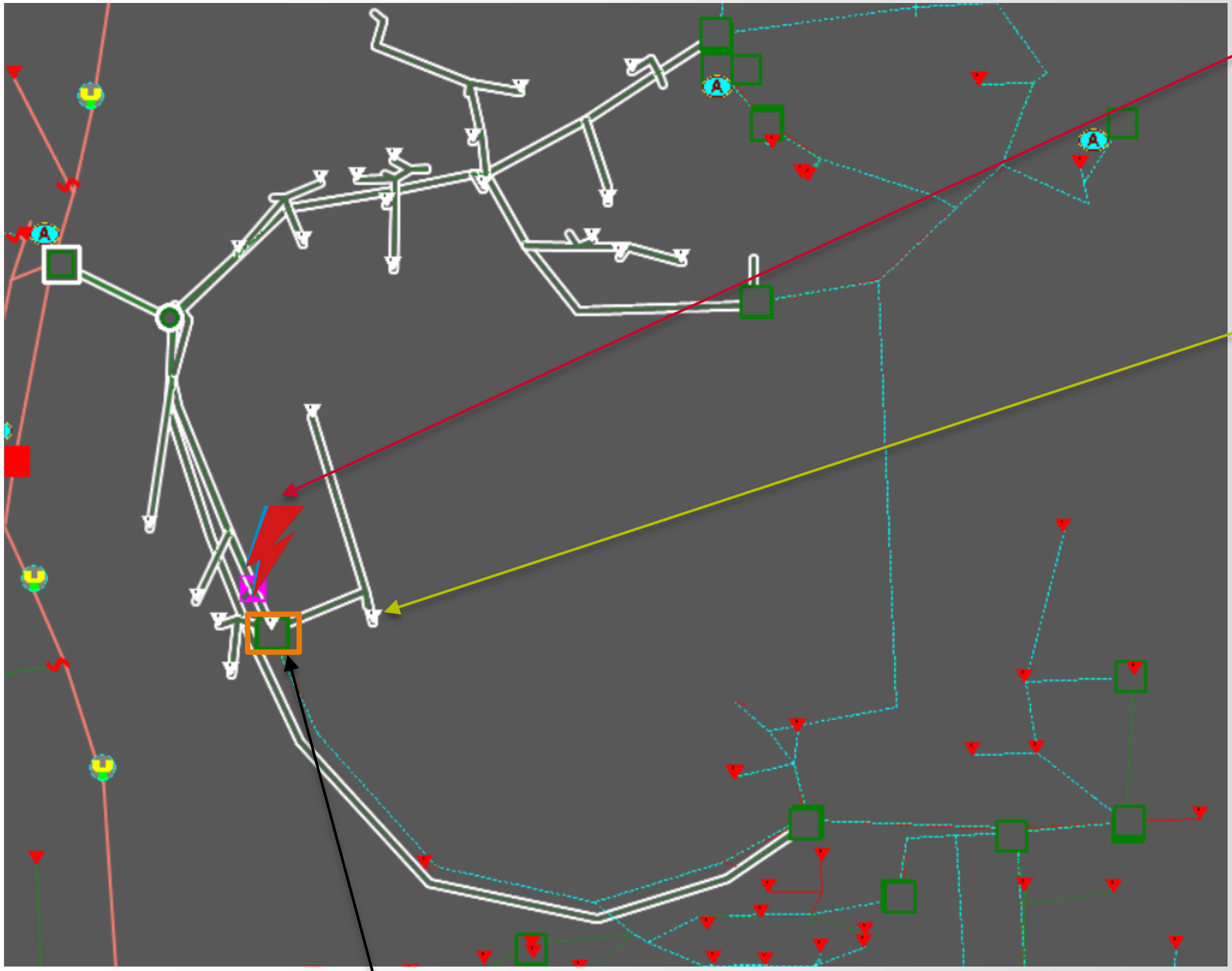
- The contribution of serving a critical load to the system performance $F(t)$ is assumed to be in proportion to its priority level
- Resilience: Cumulative service time to critical loads weighted by their priority

H. Gao, Y. Xu, Y. Chen, and C. C. Liu, "Resilience-Oriented Critical Load Restoration Using Microgrids," Accepted for IEEE Transactions Smart Grid, Special Issues on Power Grid Resilience.

Interfacing with DMS in Testbed



Feeder 117 – Fault and Outage



Fault

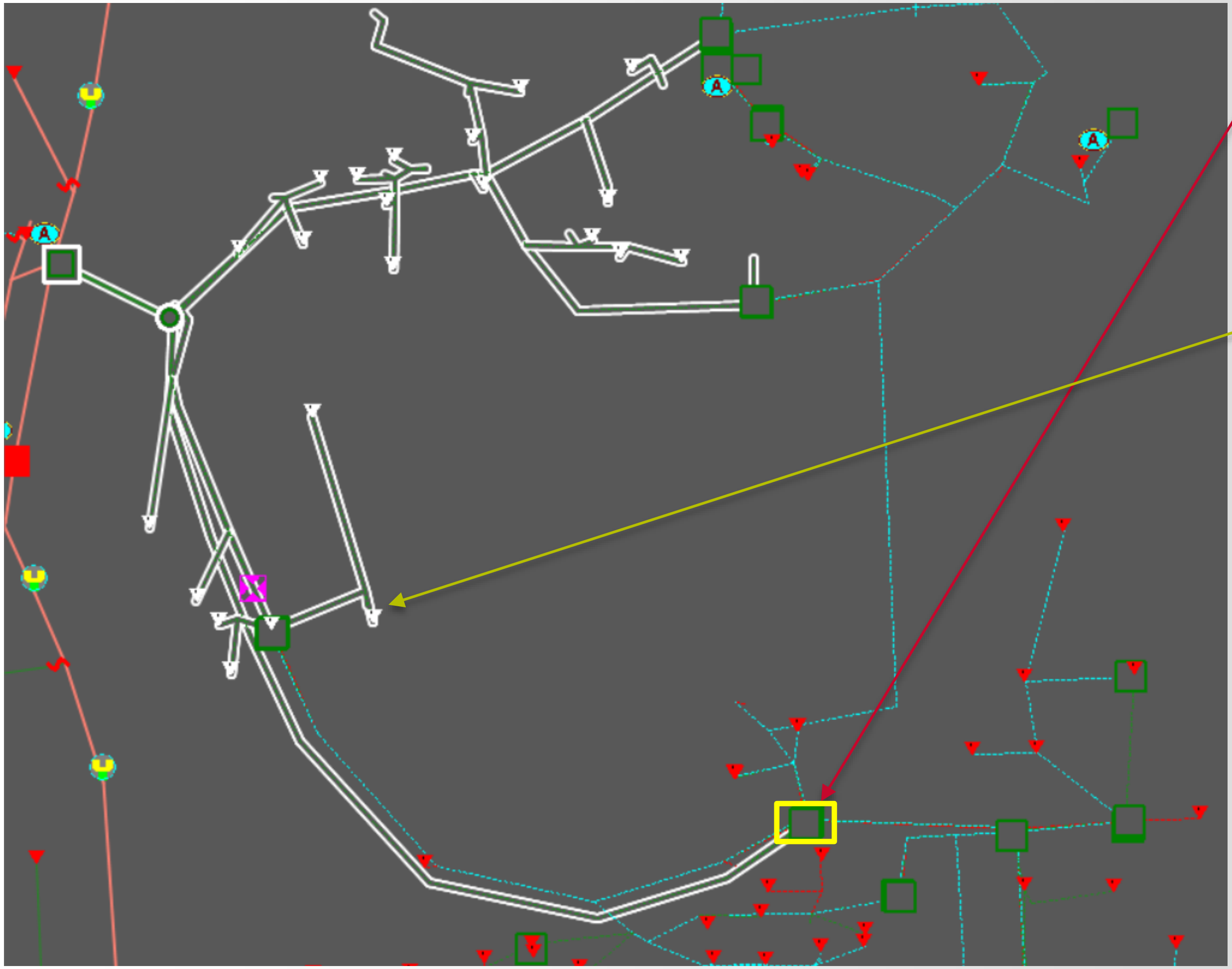
Outage marked in white

Outage due to tripping of reclosers

IDs of devices in DMS:

- TUR117_395-919894_109
- TUR117_395-919896_110
- TUR117_395-919895_111

Spanning Tree Restoration Actions



Restoration action

Outage marked in white

IDs of devices in DMS:

- TUR117_395-2425532_68
- TUR117_395-2425534_69
- TUR117_395-2425536_70

Further Information

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- Y. Xu, C. C. Liu, K. Schneider, D. Ton, “Placement of Remote-Controlled Switches to Enhance Distribution System Restoration Capability,” IEEE Trans. Power Systems, March 2016.
- Y. Xu, C. C. Liu, K. Schneider, and D. Ton, “Toward a Resilient Distribution Systems,” IEEE PES General Meeting, Jul. 2015.
- Y. Xu, C. C. Liu, H. Gao, ”Reliability Analysis of Distribution Systems Considering Service Restoration,” IEEE PES ISGT, Feb. 2015.
- J. Li, X. Y. Ma, C. C. Liu, K. Schneider, “Distribution System Restoration with Microgrid Using Spanning Tree Search, “ IEEE Trans. Power Systems, Nov. 2014, pp. 3021-3029.
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