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PNNL-33486

Energy Assurance Critical Infrastructure

Prototypical Microgrid Stability Tool

09 2022

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Kevin P. Schneider
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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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1.0 Summary

This report outlines the method PNNL developed in support of the Energy Assurance Critical Infrastructure (EACI) project to determine a general prediction of stability of an islanded microgrid. The method outlined here only provides stability predictions consistent with a conceptual design, that is a rough approximation. A more accurate and precise prediction would be determined later in the microgrid design process if it is determined that an islanded microgrid able to serve its critical electrical loads is warranted.

The first section of the report describes the prototypical distribution systems that were developed as the base networks onto which DER were attached to simulate an islanded microgrid. It was assumed the system was isolated from the bulk power system. The prototypes include features that are found on any distribution feeder such as a central line, radials, and overhead/underground cables all with varying gauges. No protection and control or power quality components were included in the prototypes as their functions were outside the scope of this work. See Section 2 and the Appendix for a detailed overview of the prototypes.

The simulation phase began with identifying key design groups with parameters of which users could classify their particular system. The groupings fall into nine groupings, System Impedance, DER Configuration, Peak Load, Load Category, Rotating Diesel Machinery, Inverter-Grid Forming, Inverter-grid Following, Load Step Increase, and Generator Loss. The available specific parameter vales are listed in Table 1. The user would choose a single value from each column that best resembles their particular system design.

Table 1: Microgrid Design Parameters

System Configuration				***DER and Generating Capacities***			***System Disturbances***	
Impedance	**DER Config.**	**Peak Load (kW)**	***Load Category***	***Diesel (kW)***	***Inverter-Grid Forming (kW)***	***Inverter-Grid Following (kW)***	***Load Step (kW)***	***DER Loss***
Low Impedance	Central DER	2500	Commercial Office	0	0	0	500	Inverter
High Impedance	Distributed DER	5000	Heavy Industrial	500	500	500	1000	Diesel
		7500	Mix 1 (Military)	1000	1000	1000	1500	
		10000	Mix 2 (Residential)	1500	1500	1500	2000	
				2000	2000	2000	2500	
				2500	2500	2500		
				3000	3000	3000		
				3500	3500	3500		
				4000	4000	4000		
				4500	4500	4500		
				5000	5000	5000		

A simulation was conducted for each viable combination of the parameters in Table 1, which numbered about 260,000 feasible systems, DER mixtures, and system disturbances. The parameters were selected to offer users the most flexibility in classifying their system, but also limited to keep the number of power system simulations to a manageable number. The total number of combinations of parameters in Table 1 is well over 500,000, however only about 260,000 are valid. For example, an invalid combination would be if a user selected a peak load of 2500 kW, and a total DER of 2000 kW. This system would be unstable due to insufficient DER capacity to meet the peak load. Invalid combinations were excluded from the list of simulated systems. The 260,000 valid simulations were completed using GridLAB-D modeling software and the results were imported and organized into a Microsoft Access database. Refer to Section 3 for a description of the database and user instructions.

An islanded microgrid was considered stable if the simulated system frequency fell within the range of 57 Hz to 60.5 Hz before a system disturbance and during the last 10 seconds after a disturbance occurred.

2.0 Prototypical Systems

To provide a means of predicting stability of an islanded microgrid, it is necessary to provide the user with as many options and system configurations as possible while also keeping the required software simulations to a manageable number. The method should also be simplistic enough such that a technician or someone not otherwise trained in microgrid design can utilize the tool effectively. To this end, the team at PNNL created and implemented the following process.

2.1.1 Power System Prototypes

The approach in designing prototypical system topologies was to include features and design aspects similar to those topologies found in actual distribution systems. Some of the prototypical design considerations are high and low impedance overhead conductors, underground cables, a central line, radial lines, single/three phase radials, and different electrical load mixes. Reference Figure 1 for the prototypical system.

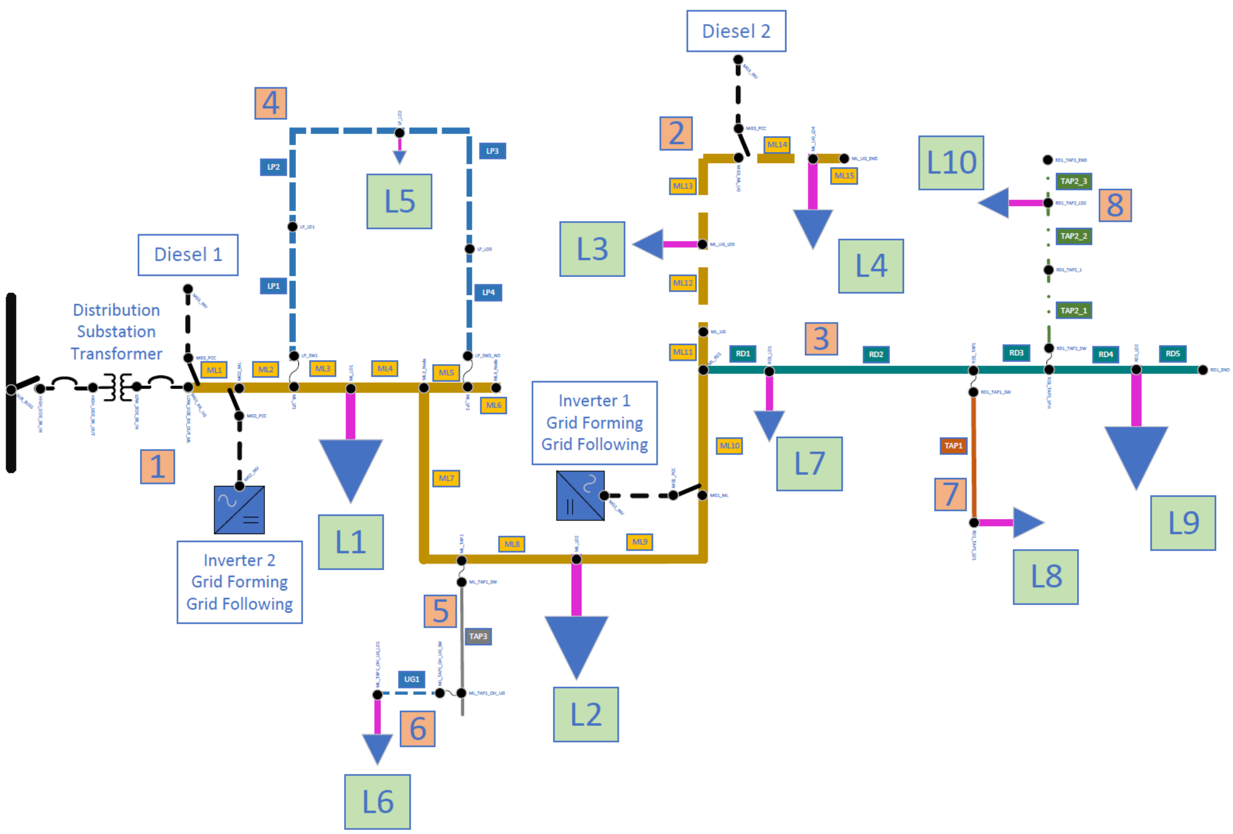

Figure 1: Prototypical Power System

The prototypical system was designed with actual power system features as follows:

1. 8 subsections comprised of varying conductor sizes (see Table 2), configurations, and span lengths.
2. 30 conductor spans (see next section and the Appendix for additional detail)
3. 4 DER – Two diesel generators and two inverter-based DER with the choice of grid following or grid forming inverters. The simulations were carried out under centralized and distributed DER configurations. For the central case, all DER were connected to a single network node located toward the front of the network. For the distributed case, the four DER were distributed throughout the network with a single DER connected to a single network node as referenced in Figure 1. The locations of the DER were held consistent for all the simulations.
4. 10 electrical loads – Electrical loads on an actual system would be more dispersed, however for convenience they were aggregated into 10 distinct loads. See the Simulation Methodology section for more detail for the loads.

Figure 2 is legend of the components contained in the prototypical system in Figure 1.

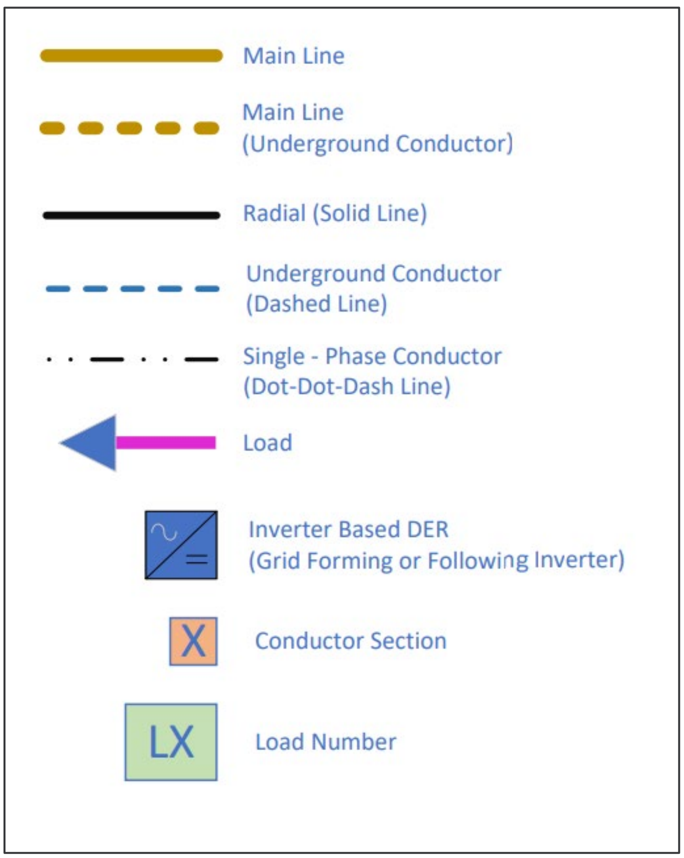

Figure 2: Prototypical System Legend

2.1.2 Network Conductors

Table 2 lists the conductors that correspond to the eight conductor sections mentioned above. They were selected in both a low impedance and high impedance option and sized commensurate with those commonly found in the field. The overhead conductors were chosen to be aluminum core steel reinforced (ACSR) according to common field deployments across distribution systems. All copper cables were chosen for underground applications, as copper is the preferred choice due to its superior conductance over aluminum. Please see the appendices for the lengths of the 30 spans.

Table 2. Conductor Sections

		Low Impedance		***High Impedance***	
Section	***Section Configuration***	*Conductors*	*Ampacity Rating*	*Conductors*	*Ampacity Rating*
1	Three-phase Overhead Primary	795 ACSR	900	336 ACSR	650
2	Three-phase UG Primary in Duct Bank	1000 Copper	630	500 Copper	532
3	Three-phase Overhead Primary Radial Tap	397 ACSR	600	4/0 ACSR	402
4	Three-phase Underground Primary Direct Bury	500 Copper UG	470	4/0 Copper UG	230
5	Three-phase Overhead Primary Radial Tap	1/0 ACSR	260	#2 ACSR	194
6	Three-phase Underground Primary Direct Bury	4/0 Copper	293	1/0 Copper UG	194
7	3-Phase Overhead Primary Radial Tap	1/0 ACSR	260	#2 ACSR	194
8	Single-phase Overhead Radial Tap	#2 ACSR	194	#4 ACSR	148

2.1.3 Electrical Load Categories

Four electrical load categories were selected to represent different types of conglomerated loads found on actual distribution systems. All 10 loads were modeled using the ZIP load coefficient method found in (Bokhari, 2014). A short description of the load categories is provided below; see the Appendix for a detailed description of the ZIP coefficients.

1. Commercial Office: The loads selected in this group might be found within commercial zonings within cities or large college campuses. Examples of loads in this category are schools, hotels, small department stores, fast food restaurants, laundromats, and to a smaller extent, residential loads.

2. Heavy Industrial: The loads in this category would be those found on industrial military installations such as shipyards, industrial parks, or large manufacturing plants. Common industrial load characteristics are those commensurate with large motor driven devices such as pumps and fans. Other industrial loads may be large heating loads such as radiative drying processes. This load category was dedicated exclusively to industrial

loads since other loads such as residential and commercial are uncommonly mixed in with industrial sites.

3. Residential Mixture: This category was weighted much heavier toward residential loads compared to the Commercial Office category. However, since commercial loas are intermingled within residential areas, fast food restaurants, laundromat, hotels, and schools were also included.

4. Military Mixture: This load grouping was assembled with equal portions of residential, commercial, office space, and industrial load types with the specific intent of modeling military installations that house service members and support full-time military missions such as major commands.

2.1.4 System Disturbances and Frequency Stability

According to (Farrokhabadi 2020, 15), a microgrid is stable if, after being subjected to a disturbance, all state variables recover to steady-state values which satisfy operational constraints and without involuntary load-shedding. For this work, a frequency falling between 57 Hz and 60.5 Hz for a period of 10-seconds before and after a disturbance is considered stable. For disturbances, the user has the choice of a loss of generation (either inverter or diesel) or a step change in load.

3.0 Simulation Methodology and Database

GridLAB-D was selected as the platform to conduct the electrical system simulations for this project. GridLAB-D was developed at Pacific Northwest National Laboratory under a DOE funded consortium of government, academia, and other national laboratories. Among all of GridLAB-D functions, those primarily used in this project were power flow and electromechanical dynamic simulations. Power flow is the hallmark of power system modeling techniques and is utilized to demonstrate point-based power system values such as voltage, system frequency, and conductor loading. Unlike power flow, electromechanical dynamic simulations measure effects on power systems over sub-second timescales and because of grid disturbances such as changes in system load or a loss of a generation source. It is these types of effects that can most destabilize an islanded microgrid.

As discussed in the Introduction, the purpose of this work was to develop a standardized process to predict microgrid stability with enough technical detail, but also with useability for less technical users such as technicians or installation energy managers. Next to developing the power system prototypes, the next step was to develop a series of design considerations including categories for network impedance, DER configuration, peak load, load category group, diesel generator capacity, inverter-based grid forming capacity, and inverter-based grid following capacity. See Table 3 for the design points that are available for user selection.

Table 3: Microgrid Design Selections

System Configuration				***DER Mixture and Generating Capacities***			***System Disturbances***	
Impedance	**DER Config.**	**Peak Load (kW)**	***Load Category***	***Diesel (kW)***	***Inverter-Grid Forming (kW)***	***Inverter-Grid Following (kW)***	***Load Step (kW)***	***DER Loss***
Low Impedance	Central DER	2500	Commercial Office	0	0	0	500	Inverter
High Impedance	Distributed DER	5000	Heavy Industrial	500	500	500	1000	Diesel
		7500	Mix 1 (Military)	1000	1000	1000	1500	
		10000	Mix 2 (Residential)	1500	1500	1500	2000	
				2000	2000	2000	2500	
				2500	2500	2500		
				3000	3000	3000		
				3500	3500	3500		
				4000	4000	4000		
				4500	4500	4500		
				5000	5000	5000		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)

3.1 Rules for Sizing DER

While the user selects total DER generation capacity in the diesel and inverter based DER categories, the simulation methodology allocates the total generation capacity in each category according to the patterns shown in Table 4. For example, if the user selects a total diesel generating capacity of 4500 kW, the simulation will assume 1-500 kW diesel unit and 2-2000 kW diesel units. The same is true for the grid forming and grid following inverter based categories.

Table 4: DER Capacity Allocation Method

Total Capacity (kW)	Number of 500 kW Units	Number of 1000 kW Units	Number of 1500 kW Units	Number of 2000 kW Units
500	1	0	0	0
1000	0	1	0	0
1500	0	0	1	0
2000	0	0	0	1
2500	1	0	0	1
3000	0	1	0	1
3500	0	0	1	1
4000	0	0	0	2
4500	1	0	0	2
5000	0	1	0	2

3.2 Rules for Loss of a Generation Source

The simulation methodology allows the user to choose between the loss of a diesel generation source or inverter-based resource. In either case, the simulation will select the largest out of the mixture. For example, if the user's diesel power generation mix is 1-2000 kW diesel and a single 500 kW diesel, the simulation will select the 2000 kW unit when conducting the diesel loss disturbance. The same is true for the inverter-based case. However, the simulation will always choose to lose the grid following inverter since an islanded system cannot exist without reference frequency and voltage values. The diesel and inverter based disturbances are always simulated independently; in other words, the user cannot run a loss of both a diesel unit and inverter based unit.

3.3 Simulation Database

Individual simulations were carried out for all valid combinations of the parameters in Table 3, which amounted to over 260,000 individual GridLAB-D simulations. All simulation results were organized in a Microsoft Access database for convenient recall.

To begin working with the database, a user will simply select the combination of parameters using the drop-down boxes in the Microsoft Access form titled, “Submit System Config and Scenario.” After the user selects the parameters, simply click the blue button (Figure 3) to execute the query and produce a result.

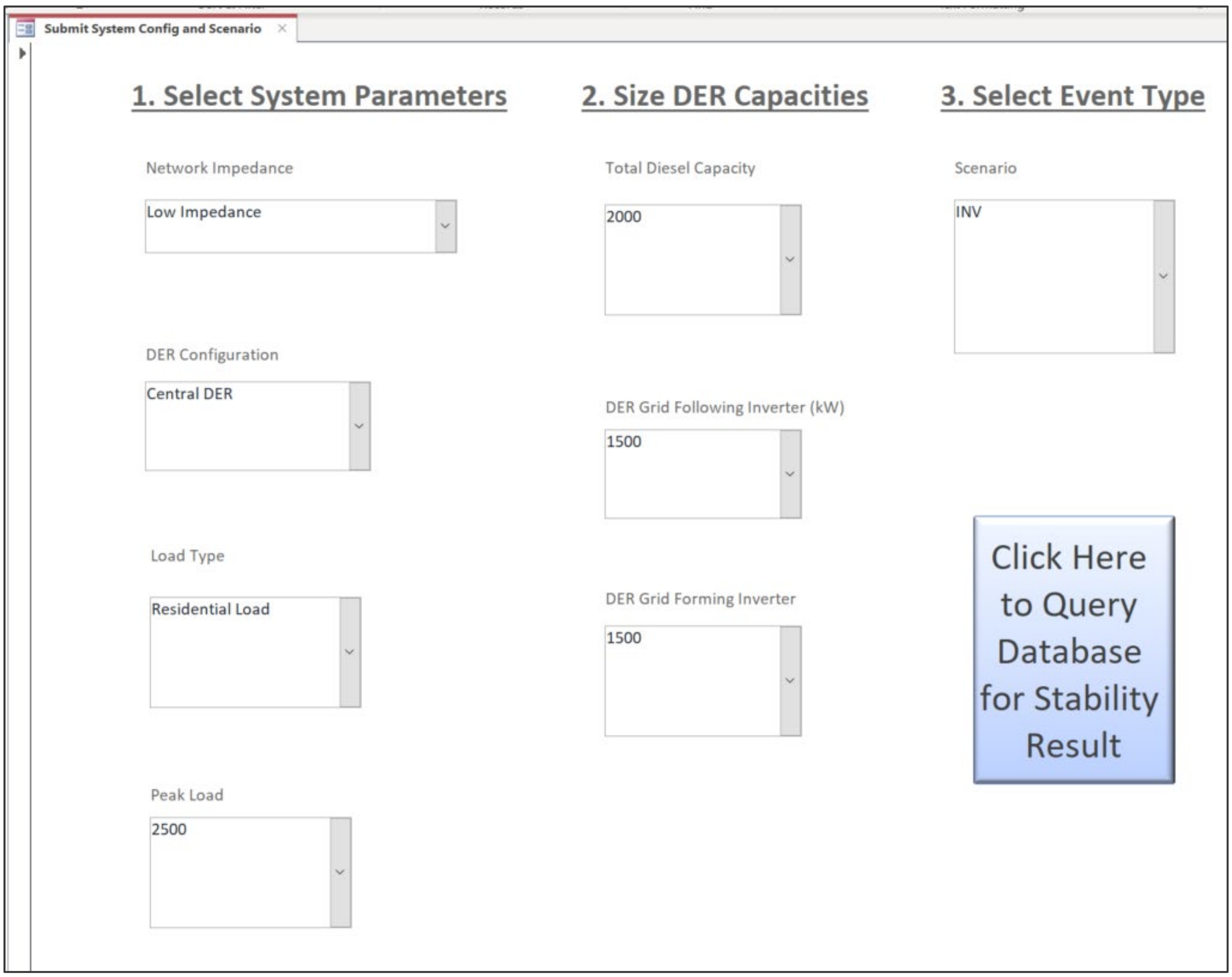

Figure 3: Database Entry Example

The output should be a single table row as illustrated below in Figure 4; the simulation result is listed in the last column. For this case, they system is “Stable.” As mentioned previously, the system would be determined stable if the pre-disturbance and post-disturbance system frequency fell within 57 Hz to 60.5 Hz before the event and during the last ten seconds after the disturbance.

Submit System Config and Scenario | Microgrid Stability Result

Network Impedance	DER Config	Load Type	Peak Load	Diesel	Grid Fol Inv	Grid Form Inv	Scenario	Pre Event Freq	Max Freq in last 1	Min Freq in last 1	Result
Low Impedance	Central DER	Residential Load	2500	2000	1500	1500	INV	60.0000000003	59.6836231725	59.683622388	Stable

Figure 4: Example Query Output

The total number of combinations in Table 2 exceeds 500,000, however as stated earlier the total number of valid combinations is about 260,000. If an invalid selection is made by the user, the database query will simply return an empty result.

4.0 References

A. Bokhari et al., "Experimental Determination of the ZIP Coefficients for Modern Residential, Commercial, and Industrial Loads," in IEEE Transactions on Power Delivery, vol. 29, no. 3, pp. 1372-1381, June 2014, doi: 10.1109/TPWRD.2013.2285096.

M. Farrokhabadi et al., "Microgrid Stability Definitions, Analysis, and Examples," in IEEE Transactions on Power Systems, vol. 35, no. 1, pp. 13-29, Jan. 2020, doi: 10.1109/TPWRS.2019.2925703.

Appendix A – Conductor and Load Data

The conductors used in the low impedance prototype are listed in Table 5.

Table 5: Low Impedance Conductors and Lengths

Segment	Span Name	Length (ft)	Conductor Description - Size
1	ML1	500	Overhead Conductor – 795
1	ML2	500	Overhead Conductor – 795
1	ML3	500	Overhead Conductor - 795
1	ML4	500	Overhead Conductor - 795
1	ML5	500	Overhead Conductor - 795
1	ML6	400	Overhead Conductor - 795
1	ML7	2000	Overhead Conductor - 795
1	ML8	900	Overhead Conductor - 795
1	ML9	1000	Overhead Conductor - 795
1	ML10	2000	Overhead Conductor - 795
1	ML11	500	Overhead Conductor - 795
2	ML12	2000	Underground Cable - 1000
2	ML13	2000	Underground Cable - 1000
2	ML14	500	Underground Cable - 1000

2	ML15	250	Underground Cable - 1000
3	RD1	1000	Overhead Conductor - 397
3	RD2	4000	Overhead Conductor - 397
3	RD3	1000	Overhead Conductor - 397
3	RD4	1000	Overhead Conductor - 397
3	RD5	750	Overhead Conductor - 397
4	LP1	1000	Underground Cable - 500
4	LP2	2000	Underground Cable - 500
4	LP3	2000	Underground Cable - 500
4	LP4	1000	Underground Cable - 500
5	TAP3	1500	Overhead Conductor – 1/0
6	UG1	750	Underground Cable – 4/0
7	TAP1	1500	Underground Cable – 1/0
8	TAP2_1	2000	Overhead Conductor - #2
8	TAP2_2	2000	Overhead Conductor - #2
8	TAP2_3	1000	Overhead Conductor - #2

The conductors used in the low impedance prototype are listed in Table 6.

Table 6: High Impedance Conductors and Lengths

Segment #	Span	Length	object conductor
1	ML1	500	Overhead Conductor - 336
1	ML2	500	Overhead Conductor - 336
1	ML3	500	Overhead Conductor - 336
1	ML4	500	Overhead Conductor - 336
1	ML5	500	Overhead Conductor - 336
1	ML6	400	Overhead Conductor - 336
1	ML7	2000	Overhead Conductor - 336
1	ML8	900	Overhead Conductor - 336
1	ML9	1000	Overhead Conductor - 336
1	ML10	2000	Overhead Conductor - 336
1	ML11	500	Overhead Conductor - 336
2	ML12	2000	Underground Cable – 500
2	ML13	2000	Underground Cable – 500
2	ML14	500	Underground Cable – 500
2	ML15	250	Underground Cable – 500

3	RD1	1000	Overhead Conductor – 4/0
3	RD2	4000	Overhead Conductor – 4/0
3	RD3	1000	Overhead Conductor – 4/0
3	RD4	1000	Overhead Conductor – 4/0
3	RD5	750	Overhead Conductor – 4/0
4	LP1	1000	Underground Cable – 4/0
4	LP2	2000	Underground Cable – 4/0
4	LP3	2000	Underground Cable – 4/0
4	LP4	1000	Underground Cable – 4/0
5	TAP3	1500	Overhead Conductor #2
6	UG1	750	Underground Cable 1/0
7	TAP1	1500	Overhead Conductor #2
8	TAP2_1	2000	Overhead Conductor #4
8	TAP2_2	2000	Overhead Conductor #4
8	TAP2_3	1000	Overhead Conductor #4

Four electrical load categories were used in the simulation environment, commercial industrial, residential, and a mixture. Refer to Section 2 for a description. Table 7 lists the type of load that was used for each of the ten loads for the four load categories.

Table 7: Load Designations for load Categories

		Load 1	Load 2	Load 3	Load 4	Load 5	Load 6	Load 7	Load 8	Load 9	Load 10
1 Commercial	Load Type	School	Hotel	Hotel	School	Small Dept Store	Fast Food	Laundry	Fast Food	Small Dept Store	Res A
	Phase	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	AN
	System Voltage	7200	7200	7200	7200	7200	7200	7200	7200	7200	7200
2 Industrial	Load Type	Indus.	Indus.	Indus.	Indus.	Indus.	Indus.	Indus.	Indus.	Indus.	Indus.
	Phase	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	AN
	System Voltage	7200	7200	7200	7200	7200	7200	7200	7200	7200	7200
3 Residential	Load Type	School	Res A	Hotel	Res C	Res D	Fast Food	Laundry	Res E	Res F	Res B
	Phase	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	AN
	System Voltage	7200	7200	7200	7200	7200	7200	7200	7200	7200	7200
4 Mixture	Load Type	School	Res A	Hotel	Industrial	Small Dept Store	Fast Food	Laundry	Res B	Exclusive Svc	Res C
	Phase	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	ABCN	AN
	System Voltage	7200	7200	7200	7200	7200	7200	7200	7200	7200	7200

In Section 3, it was noted that the load coefficient method in (Bokhari, 2014) was used for modeling the electrical load objects in GridLAB-D. Table 8 lists the coefficients as they are found in (Bokhari, 2014) and those used in the load objects.

Table 8: ZIP Load Coefficients

		Active (P)			Reactive (Q)			Power Factor		
Load Type		Z_P	I_P	P_P	Z_q	I_q	P_q	Z_{PF}	I_{PF}	P_{PF}
Residential	A	1.5	-2.31	1.81	7.41	-11.97	5.55	0.20	-0.19	0.31
	B	1.57	-2.48	1.91	9.28	-15.29	7.01	0.17	-0.16	0.26
	C	1.56	-2.49	1.93	10.1	-16.75	7.65	0.15	-0.15	0.24
	D	1.31	-1.94	1.63	9.2	-15.27	7.07	0.14	-0.13	0.22
	E	0.96	-1.17	1.21	6.28	-10.16	4.88	0.15	-0.11	0.24
	F	1.18	-1.64	1.47	8.29	-13.67	6.38	0.14	-0.12	0.22
Small Commercial	Small Dept Store	0.27	-0.33	1.06	5.48	-9.7	5.22	0.05	-0.03	0.20
	Fast Food	0.69	0.04	0.27	1.82	-2.24	1.43	0.35	0.02	0.19
	Laundromat	0.77	-0.84	1.07	8.09	-13.65	6.56	0.09	-0.06	0.16
	Exclusive Service	0.55	0.24	0.21	0.55	-0.09	0.54	0.71	0.94	0.36
Large Commercial	School	0.4	-0.41	1.01	4.43	-7.98	4.56	0.09	-0.05	0.22
	Hotel	0.76	-0.52	0.76	6.92	-11.75	5.83	0.11	-0.04	0.99
Industrial		1.21	-1.61	1.41	4.35	-7.08	3.72	0.27	-0.22	0.94

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