Benchmark Systems

Modeling Description

**Abstract:** This document describes the modeling of the Benchmark Examples using the OpenDSS Library from the Typhoon HIL toolchain. The main goal of these systems is to support a starting point for the usage of the library applying its key features. The library modeling technique/features are applied according to the electrical system characteristics in the study.

Contents

[IEEE Systems 1](#_Toc131148813)

[IEEE 13 bus Feeder (Distribution Systems) 1](#_Toc131148814)

[Results 3](#_Toc131148815)

[Modeling Data 4](#_Toc131148816)

[References 6](#_Toc131148817)

[CIGRE Systems 6](#_Toc131148818)

[CIGRE European Medium Voltage (Distribution Systems) 6](#_Toc131148819)

[Results 7](#_Toc131148820)

[Modeling Data 8](#_Toc131148821)

[References 9](#_Toc131148822)

[OTHER Systems 9](#_Toc131148823)

[BANSHEE DISTRIBUTION NETWORK (MICROGRID) 9](#_Toc131148824)

[Results 10](#_Toc131148825)

[Modeling Data 12](#_Toc131148826)

[References 13](#_Toc131148827)

# IEEE Systems

## IEEE 13 bus Feeder (Distribution Systems)

The IEEE 13 Bus feeder is commonly employed in studies involving distribution systems. Despite being a small system, the feeder has interesting characteristics [1]:

* Short and relatively loaded for a 4.16 kV feeder:
  + Unbalanced spot and distributed loads (~3466 MW and 2102 MVAR);
* Variety Overhead and Underground lines topologies:
  + Ten branches (~2.5 km of lines)
* Voltage Regulation equipment:
  + One series voltage regulator (three single-phase transformers);
  + Shunt Capacitor banks (one single-phase and one three-phase bank).

The feeder topology is shown in Figure 1. The system mainly operates at 4.16 kV. The reference provides one substation transformer data operating at 115 kV, but it is not considered in the modeling. Three single-phase voltage regulators are used between the #650 and #632 buses. At the default configuration, the transformers are parameterized using a line voltage drop compensation, but the current stage of the library does not support this feature. A modification on the voltage reference of the regulator is implemented to match the secondary level of the voltage regulator.

The inherent unbalance of the feeder is preserved through the load connections and line representation. All the loads from the feeder are modeled using a constant impedance approach. The lines are modeled using a matrix representation from linecodes feature from the library. All modeling data is provided in the following subsections.

The power flow results compared in Table 2 and Table 1 show a close match between the model and the reference, even with the abovementioned modifications. Table 2 compares the voltages at the load nodes. The DSS column refers to the results obtained from the SymDSS component from the Schematic Editor, and the SCADA column is the steady state voltages from the runtime simulation.

|  |
| --- |
| A moon in the sky  Description automatically generated with low confidence |

Figure 1 – Single Line diagram of the IEEE 13 Bus Feeder.

### Results

Table 1. Power Flow – System Input.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **#** | **IEEE**  **Phase A** | **DSS**  **Phase A** | **SCADA**  **Phase A** | **IEEE**  **Phase B** | **DSS**  **Phase B** | **SCADA**  **Phase B** | **IEEE**  **Phase C** | **DSS**  **Phase C** | **SCADA**  **Phase C** |
| **kW** | 1251.398 | 1177.700 | 1135.211 | 977.332 | 1037.700 | 1016.234 | 1348.461 | 1301.500 | 1377.268 |
| **kvar** | 681.570 | 650.500 | 648.132 | 373.418 | 407.200 | 400.899 | 669.784 | 705.300 | 764.008 |
| **kVA** | 1424.968 | 1345.400 | 1307.203 | 1046.241 | 1114.700 | 1092.452 | 1505.642 | 1480.300 | 1574.984 |
| **PF** | 0.8782 | 0.8753 | 0.868 | 0.9341 | 0.9309 | 0.9302 | 0.8956 | 0.8792 | 0.8745 |

Table 2. Power Flow – Load Voltages Magnitudes.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Bus/Node** | **Phase** | **IEEE** | **DSS** | **SCADA** | **Bus/Node** | **Phase** | **IEEE** | **DSS** | **SCADA** |
| **#650** | Va | 1.0000 | 0.9999 | 1.0021 | **#671** | Va | 0.9900 | 0.9454 | 0.9295 |
| Vb | 1.0000 | 1.0002 | 0.9999 | Vb | 1.0529 | 1.0536 | 1.0356 |
| Vc | 1.0000 | 0.9998 | 0.9979 | Vc | 0.9778 | 0.9901 | 1.0197 |
| **#632** | Va | 1.0210 | 0.9928 | 0.9929 | **#652** | Va | 0.9825 | 0.9382 | 0.9182 |
| Vb | 1.0420 | 1.0451 | 1.0140 | Vb | -- | -- | -- |
| Vc | 1.0174 | 1.0176 | 1.0444 | Vc | -- | -- | -- |
| **#634** | Va | 0.9940 | 0.9668 | 0.9332 | **#611** | Va | -- | -- | -- |
| Vb | 1.0218 | 1.0239 | 0.9962 | Vb | -- | -- | -- |
| Vc | 0.9960 | 0.9963 | 1.0558 | Vc | 0.9738 | 0.9862 | 1.0156 |
| **#645** | Va | -- | -- | -- | **#692** | Va | 0.9900 | 0.9453 | 1.0190 |
| Vb | 1.0329 | 1.0355 | 1.0298 | Vb | 1.0529 | 1.0536 | --\* |
| Vc | 1.0155 | 1.0157 | --\* | Vc | 0.9777 | 0.9900 | 0.9288 |
| **#646** | Va | -- | -- | -- | **#675** | Va | 0.9835 | 0.9394 | 0.9215 |
| Vb | 1.0311 | 1.0337 | 1.0240 | Vb | 1.0553 | 1.0557 | 1.0385 |
| Vc | 1.0134 | 1.0136 | 1.0333 | Vc | 0.9758 | 0.9881 | 1.0182 |

Table 3. Power Flow – Load Voltages Errors.

| **Bus/Node** | **Phase** | **DSS** | **SCADA** | **Bus/Node** | **Phase** | **DSS** | **SCADA** |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **#650** | Va | 0.01% | -0.21% | **#671** | Va | 4.51% | 6.11% |
| Vb | -0.02% | 0.01% | Vb | -0.07% | 1.64% |
| Vc | 0.02% | 0.21% | Vc | -1.26% | -4.29% |
| **#632** | Va | 2.76% | 2.75% | **#652** | Va | 4.50% | 6.54% |
| Vb | -0.30% | 2.69% | Vb | -- | -- |
| Vc | -0.02% | -2.65% | Vc | -- | -- |
| **#634** | Va | 2.74% | 6.12% | **#611** | Va | -- | -- |
| Vb | -0.21% | 2.51% | Vb | -- | -- |
| Vc | -0.03% | -6.00% | Vc | -1.27% | -4.29% |
| **#645** | Va | -- | -- | **#692** | Va | 4.52% | -2.93% |
| Vb | -0.25% | 0.30% | Vb | -0.07% | --\* |
| Vc | -0.02% | --\* | Vc | -1.26% | 5.00% |
| **#646** | Va | -- | -- | **#675** | Va | 4.49% | 6.30% |
| Vb | -0.25% | 0.69% | Vb | -0.04% | 1.59% |
| Vc | -0.02% | -1.96% | Vc | -1.26% | -4.35% |

### Modeling Data

Table 4. Line Segment Data.

| **Line** | **From (#node)** | **To (#node)** | **Config ID** | **km** | **Phases** |
| --- | --- | --- | --- | --- | --- |
| **Line\_650632** | #650 | #632 | 601 | 0.610 | ABC |
| **Line\_632645** | #632 | #645 | 603 | 0.152 | BC |
| **Line\_632633** | #632 | #633 | 602 | 0.152 | ABC |
| **XFM-1** | #633 | #634 | 500 kVA – 4.16/0.48 kV (Ynyn); Z=1.1+2% | | |
| **Line\_645646** | #645 | #646 | 603 | 0.091 | BC |
| **Line\_632671** | #632 | #671 | 601 | 0.610 | ABC |
| **Line\_671684** | #671 | #684 | 604 | 0.091 | AC |
| **Line\_671680** | #671 | #680 | 601 | 0.305 | ABC |
| **Switch** | #671 | #692 | Static Switch (ABC) | | |
| **Line\_684652** | #684 | #652 | 607 | 0.244 | A |
| **Line\_684611** | #684 | #611 | 605 | 0.091 | C |
| **Line\_692675** | #692 | #675 | 606 | 0.152 | ABC |

Table 5. Load Data.

| **Node** | **SA**  **[kVA]** | **FPA** | **SB**  **[kVA]** | **FPB** | **SC**  **[kVA]** | **FPC** | **Notes** |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **#634** | 194.16 | 0.82 | 150.00 | 0.80 | 150.00 | 0.80 | Spot Load (Y ABC) |
| **#645** | -- | -- | 211.01 | 0.81 | -- | -- | Spot Load (B) |
| **#646** | -- | -- | 265.19 | 0.87 | -- | -- | Spot Load (BC) |
| **#652** | 154.21 | 0.83 | -- | -- | -- | -- | Spot Load (A) |
| **#671** | 443.42 | 0.87 | 443.42 | 0.87 | 443.42 | 0.87 | Spot Load (D ABC) |
| **#675** | 520.89 | 0.93 | 90.69 | 0.75 | 359.23 | 0.81 | Spot Load (Y ABC) |
| **#692** | -- | -- | -- | -- | 227.38 | 0.75 | Spot Load (AC) |
| **#611** | -- | -- | -- | -- | 187.88 | 0.90 | Spot Load (C) |
| **#632** | 19.72/2 | 0.86 | 76.16/2 | 0.87 | 135.33/2 | 0.86 | Distr. Load (Y ABC) |
| **#671** | 19.72/2 | 0.86 | 76.16/2 | 0.87 | 135.33/2 | 0.86 | Distr. Load (Y ABC) |
| **#675** | 200 | -- | 200 | -- | 200 | -- | Capacitor (Y ABC) |
| **#611** | -- | -- | -- | -- | 100 | -- | Capacitor (C) |

Table 6. Impedances for Configuration 601 (Linecode CONFIG\_601).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Resistance Matrix (Ω/km)** | | | **Reactance Matrix (Ω/km)** | | | **Capacitance Matrix (nF/km)** | | |
| 0.2153 |  |  | 0.6325 |  |  | 10.3836 |  |  |
| 0.0969 | 0.2097 |  | 0.3117 | 0.6511 |  | -3.2896 | 9.8230 |  |
| 0.0982 | 0.0954 | 0.2121 | 0.0982 | 0.2392 | 0.6430 | -2.0760 | -1.2225 | 9.2938 |

Table 7. Impedances for Configuration 602 (Linecode CONFIG\_602).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Resistance Matrix (Ω/km)** | | | **Reactance Matrix (Ω/km)** | | | **Capacitance Matrix (nF/km)** | | |
| 0.4676 |  |  | 0.7341 |  |  | 9.3933 |  |  |
| 0.0982 | 0.4645 |  | 0.2632 | 0.7446 |  | -1.7829 | 8.5371 |  |
| 0.0969 | 0.0954 | 0.4621 | 0.3117 | 0.2392 | 0.7526 | -2.7864 | -1.0859 | 8.9411 |

Table 8. Impedances for Configuration 603 (Linecode CONFIG\_603).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Resistance Matrix (Ω/km)** | | | **Reactance Matrix (Ω/km)** | | | **Capacitance Matrix (nF/km)** | | |
| -- |  |  | -- |  |  | -- |  |  |
| -- | 0.8261 |  | -- | 0.8371 |  | -- | 7.7627 |  |
| -- | 0.1284 | 0.8226 | -- | 0.2853 | 0.8431 | -- | -1.4833 | 7.6904 |

Table 9. Impedances for Configuration 604 (Linecode CONFIG\_604).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Resistance Matrix (Ω/km)** | | | **Reactance Matrix (Ω/km)** | | | **Capacitance Matrix (nF/km)** | | |
| 0.8226 |  |  | 0.8431 |  |  | 7.6904 |  |  |
| -- | -- |  | -- | -- |  | -- | -- |  |
| 0.1284 | -- | 0.8261 | 0.2853 | -- | 0.8371 | -1.4833 | -- | 7.7627 |

Table 10. Impedances for Configuration 605 (Linecode CONFIG\_605).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Resistance Matrix (Ω/km)** | | | **Reactance Matrix (Ω/km)** | | | **Capacitance Matrix (nF/km)** | | |
| -- |  |  | -- |  |  | -- |  |  |
| -- | -- |  | -- | -- |  | -- | -- |  |
| -- | -- | 0.8259 | -- | -- | 0.8373 | -- | -- | 7.4489 |

Table 11. Impedances for Configuration 606 (Linecode CONFIG\_606).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Resistance Matrix (Ω/km)** | | | **Reactance Matrix (Ω/km)** | | | **Capacitance Matrix (nF/km)** | | |
| 0.4960 |  |  | 0.2773 |  |  | 159.6977 |  |  |
| 0.1983 | 0.4903 |  | 0.0204 | 0.2511 |  | -- | 159.6977 |  |
| 0.1770 | 0.1983 | 0.4960 | -0.0089 | 0.0204 | 0.2773 | -- | -- | 159.6977 |

Table 12. Impedances for Configuration 607 (Linecode CONFIG\_607).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Resistance Matrix (Ω/km)** | | | **Reactance Matrix (Ω/km)** | | | **Capacitance Matrix (nF/km)** | | |
| 0.8342 |  |  | 0.3184 |  |  | 148.3273 |  |  |
| -- | -- |  | -- | -- |  | -- | -- |  |
| -- | -- | -- | -- | -- | -- | -- | -- | -- |

Table 13. Voltage Regulator Settings.

|  |  |  |  |
| --- | --- | --- | --- |
| **Regulator ID:** | 1 |  |  |
| **Line Segment:** | 650 - 632 |  |  |
| **Location:** | 50 |  |  |
| **Phases:** | A - B -C |  |  |
| **Connection:** | 3-Ph,LG |  |  |
| **Monitoring Phase:** | A-B-C |  |  |
| **Bandwidth:** | 2.0 volts |  |  |
| **PT Ratio:** | 20 |  |  |
| **Primary CT Rating:\*** | 700 |  |  |
| **Compensator Settings:\*** | Ph-A | Ph-B | Ph-C |
| **R - Setting:\*** | 3 | 3 | 3 |
| **X - Setting:\*** | 9 | 9 | 9 |
| **Volltage Level:** | 122 | 122 | 122 |

### References

[1] – IEEE 13 Bus Feeder (<https://cmte.ieee.org/pes-testfeeders/resources/>)

# CIGRE Systems

## CIGRE European Medium Voltage (Distribution Systems)

The CIGRE Medium Voltage distribution network is derived from a physical network in southern Germany [2], which supplies a small town and the surrounding rural area. In the European version, the modeling does not include unbalances on lines and loads.

Figure 2 shows the topology of the feeder. The system operates at 20 kV 50 Hz via separate transformers (T1 and T2) from the 110 kV transmission network. The topology can be modified between radial/radial/meshed configurations through S1, S2, and S3 switches.

The data modeling is presented in the following subsections. All lines are symmetrical, and the loads are represented as constant impedance. A fixed tap at the transformers T1 and T2 is set manually on the transformer parameterization (without voltage regulator).

The power flow results in the Results subsection show a good match between the OpenDSS and SCADA models compared to the reference.

|  |
| --- |
|  |

Figure 2 – Single Line diagram of the CIGRE European MV Feeder.

### Results

Table 14. Power Flow – Load Voltages Magnitudes.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Bus** | **CIGRE** | **DSS** | **SCADA** | **Bus** | **CIGRE** | **DSS** | **SCADA** |
| **#0** | 1.0000 | 1.0007 | 1.0004 | **#8** | 0.9665 | 0.9625 | 0.9643 |
| **#1** | 1.0260 | 1.0213 | 1.0227 | **#9** | 0.9655 | 0.9616 | 0.9634 |
| **#2** | 1.0045 | 1.0003 | -- | **#10** | 0.9645 | 0.9605 | 0.9623 |
| **#3** | 0.9715 | 0.9674 | 0.9675 | **#11** | 0.9645 | 0.9603 | 0.9621 |
| **#4** | 0.9700 | 0.9657 | 0.9697 | **#12** | 1.0020 | 1.0004 | 1.0036 |
| **#5** | 0.9690 | 0.9646 | 0.9664 | **#13** | 0.9970 | 0.9956 | 0.9986 |
| **#6** | 0.9675 | 0.9632 | 0.9651 | **#14** | 0.9940 | 0.9929 | 0.9958 |
| **#7** | 0.9665 | 0.9622 | 0.9640 |  | | | |

Table 15. Power Flow – Load Voltages Errors.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Bus** | **DSS** | **SCADA** | **Bus** | **DSS** | **SCADA** |
| **#0** | -0.07% | -0.04% | **#8** | 0.42% | 0.23% |
| **#1** | 0.46% | 0.32% | **#9** | 0.41% | 0.22% |
| **#2** | 0.42% | -- | **#10** | 0.42% | 0.23% |
| **#3** | 0.43% | 0.41% | **#11** | 0.44% | 0.25% |
| **#4** | 0.44% | 0.03% | **#12** | 0.16% | -0.16% |
| **#5** | 0.46% | 0.27% | **#13** | 0.14% | -0.16% |
| **#6** | 0.44% | 0.25% | **#14** | 0.11% | -0.18% |
| **#7** | 0.44% | 0.26% |  | | |

Table 16. Power Flow – System Input.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Meas.** | **CIGRE** | **DSS** | | **SCADA** | |
| **Value** | **Error** | **Value** | **Error** |
| **P (MW)** | 45.9076 | 45.5472 | 0.79% | 46.5141 | -1.32% |
| **Q (Mvar)** | 16.5096 | 16.8198 | -1.88% | 15.7301 | 4.72% |
| **S (MVA)** | 48.7860 | 48.5536 | 0.48% | 49.1018 | -0.65% |
| **PF** | 0.9410 | 0.9381 | 0.31% | 0.9473 | -0.67% |

### Modeling Data

Table 17. Line Segment Data.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Line** | **From**  **(#Bus)** | **To**  **(#Bus)** | **R1 (Ω/km)** | **X1 (Ω/km)** | **C1 (nF/km)** | **R0 (Ω/km)** | **x0 (Ω/km)** | **C0 (nF/km)** | **km** |
| **Line\_1** | #1 | #2 | 0.501 | 0.716 | 151.175 | 0.817 | 1.598 | 151.175 | 2.82 |
| **Line\_2** | #2 | #3 | 0.501 | 0.716 | 151.175 | 0.817 | 1.598 | 151.175 | 4.42 |
| **Line\_3** | #3 | #4 | 0.501 | 0.716 | 151.175 | 0.817 | 1.598 | 151.175 | 0.61 |
| **Line\_4** | #4 | #5 | 0.501 | 0.716 | 151.175 | 0.817 | 1.598 | 151.175 | 0.56 |
| **Line\_5** | #5 | #6 | 0.501 | 0.716 | 151.175 | 0.817 | 1.598 | 151.175 | 1.54 |
| **Line\_6** | #6 | #7 | 0.501 | 0.716 | 151.175 | 0.817 | 1.598 | 151.175 | 0.24 |
| **Line\_7** | #7 | #8 | 0.501 | 0.716 | 151.175 | 0.817 | 1.598 | 151.175 | 1.67 |
| **Line\_8** | #8 | #9 | 0.501 | 0.716 | 151.175 | 0.817 | 1.598 | 151.175 | 0.32 |
| **Line\_9** | #9 | #10 | 0.501 | 0.716 | 151.175 | 0.817 | 1.598 | 151.175 | 0.77 |
| **Line\_10** | #10 | #11 | 0.501 | 0.716 | 151.175 | 0.817 | 1.598 | 151.175 | 0.33 |
| **Line\_11** | #11 | #4 | 0.501 | 0.716 | 151.175 | 0.817 | 1.598 | 151.175 | 0.49 |
| **Line\_12** | #3 | #8 | 0.501 | 0.716 | 151.175 | 0.817 | 1.598 | 151.175 | 1.30 |
| **Line\_13** | #12 | #13 | 0.510 | 0.366 | 10.097 | 0.658 | 1.611 | 4.0743 | 4.89 |
| **Line\_14** | #13 | #14 | 0.510 | 0.366 | 10.097 | 0.658 | 1.611 | 4.0743 | 2.99 |
| **Line\_15** | #14 | #8 | 0.510 | 0.366 | 10.097 | 0.658 | 1.611 | 4.0743 | 2.00 |

Table 18. Transformers T1 and T2 data.

|  |  |
| --- | --- |
| **Rated Primary Voltage:** | 110 kV |
| **Rated Secondary Voltage:** | 20 kV |
| **Connection:** | Dyn |
| **Rated Power:** | 25 MVA |
| **R:** | 1 % |
| **X:** | 12 % |

Table 19. Load Data.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Bus** | **Residential** | | **Industrial** | |
| **S [kVA]** | **PF** | **S [kVA]** | **PF** |
| **#1** | 15300 | 0.98 | 5100 | 0.95 |
| **#2** | --- | --- | --- | --- |
| **#3** | 285 | 0.97 | 265 | 0.85 |
| **#4** | 445 | 0.97 | --- | --- |
| **#5** | 750 | 0.97 | --- | --- |
| **#6** | 565 | 0.97 | --- | --- |
| **#7** | --- | --- | 90 | 0.85 |
| **#8** | 605 | 0.97 | --- | --- |
| **#9** | --- | --- | 675 | 0.85 |
| **#10** | 490 | 0.97 | 80 | 0.85 |
| **#11** | 340 | 0.97 | --- | --- |
| **#12** | 15300 | 0.98 | 5280 | 0.95 |
| **#13** | --- | --- | 40 | 0.85 |
| **#14** | 215 | 0.97 | 390 | 0.85 |

### References

[2] - [TF C6.04.02 : TB 575 -- Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources.](http://www.e-cigre.org/Order/select.asp?ID=16639)

# OTHER Systems

## BANSHEE DISTRIBUTION NETWORK (MICROGRID)

The Banshee benchmark corresponds to a real-life small industrial facility, which reproduces typical microgrid challenges worldwide. Three utility feeders service the power plant at 13.8 kV levels (Figure 1) that may interconnect through normally open tie switches. Twenty-two (22) distribution transformers reduce the 13.8 kV to service voltages of 4.16 kV, 480 V, and 208 V.

Eighteen (18) aggregated low voltage loads (480 V and 208 V) are classified as critical, priority, or interruptible (all loads are modeled as constant power mode). In that way, several circuit breakers perform a load-shedding logic on the microgrid controller according to the load classification. All circuit breakers on the power plant are modeled as static switches, although they should be changed to controlled switches according to the model applications.

Banshee also includes two large induction motors (200 HP) connected with the P1 and P6 loads. However, as motors are not present in the current Typhoon OpenDSS library, it still needs to be considered on the model in future versions. The same is applied to the PV generation connected to bus #202. In this context, BESS and synchronous generators of the power plant also are not used in this modeling version.

|  |
| --- |
| Graphical user interface, application  Description automatically generated |

Figure 3 – Single Line diagram of the Banshee Microgrid.

The power flow results compared in Table 20 – Table 22 show the match between the Typhoon model and the reference. The DSS column refers to the results obtained from the SymDSS component from the Schematic Editor, and the SCADA column is the steady state voltages from the runtime simulation.

It’s worth mentioning two points about the results:

* Several TLM core coupling components divide the model resources due to the power plant size. That kind of core coupling has some advantages in terms of stability compared to the ITM method, but it adds shunt capacitance to the model, which can be significant if the inductance of the TLM is small. To minimize that behavior, all TLM is placed inside the transformers. Even though those capacitors impact the system, as shown in Table 20 and Table 22, when significative errors are observed only on the SCADA tab. On the power flow impact, it is possible to see differences of around 30% in the reactive power flowing in some circuits. From the voltage viewpoint, it is also possible to check the capacitors' impact in over-voltages in some buses, in the worst cases, assuming values greater than 1.0 pu.
* CB102 flow has significant errors in both DSS and SCADA tabs. Comparing the data entry of the source code from the reference was noted a different input for the reactive power in a load of this branch. The model will use the load value from the reference paper instead.

### Results

Table 20. Power Flow at feeders PCC.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Circuit Breaker** | **REF.** | | **DSS** | | **SCADA** | |
| **MW** | **Mvar** | **MW** | **Mvar** | **MW** | **Mvar** |
| **CB101** | 1.37 | 0.70 | 1.36 | 0.71 | 1.37 | 0.68 |
| **CB102** | 2.53 | 1.09 | 2.48 | 1.39 | 2.52 | 1.40 |
| **CB103** | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | -0.02 |
| **CB201** | 2.67 | 1.40 | 2.64 | 1.40 | 2.66 | 1.40 |
| **CB202** | 1.28 | 0.65 | 1.27 | 0.65 | 1.28 | 0.86 |
| **CB203** | 1.55 | 0.76 | 1.54 | 0.79 | 1.55 | 0.92 |
| **CB301** | 1.46 | 0.74 | 1.46 | 0.75 | 1.47 | 0.70 |
| **CB302** | 0.55 | 0.29 | 0.55 | 0.28 | 0.55 | 0.27 |
| **CB303** | 0.74 | 0.39 | 0.73 | 0.39 | 0.74 | 0.39 |
| **CB304** | 0.91 | 0.46 | 0.91 | 0.47 | 0.91 | 0.46 |

Table 21. Power Flow errors at feeders PCC.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Circuit Breaker** | **DSS** | | **SCADA** | |
| **MW** | **Mvar** | **MW** | **Mvar** |
| **CB101** | 0.73% | -1.43% | 0.00% | 2.86% |
| **CB102** | 1.98% | -27.52% | 0.40% | -28.44% |
| **CB103** | -- | -- |  |  |
| **CB201** | 1.12% | 0.00% | 0.37% | 0.00% |
| **CB202** | 0.78% | 0.00% | 0.00% | -32.31% |
| **CB203** | 0.65% | -3.95% | 0.00% | -21.05% |
| **CB301** | 0.00% | -1.35% | -0.68% | 5.41% |
| **CB302** | 0.00% | 3.45% | 0.00% | 6.90% |
| **CB303** | 1.35% | 0.00% | 0.00% | 0.00% |
| **CB304** | 0.00% | -2.17% | 0.00% | 0.00% |

Table 22. Load Voltages Magnitudes and errors.

| **Load ID** | **REF**  **Voltage** | **DSS** | | **SCADA** | |
| --- | --- | --- | --- | --- | --- |
| **Voltage** | **Error** | **Voltage** | **Error** |
| **C1** | 0.978 | 0.967 | 1.08% | 0.976 | 0.20% |
| **C2** | 0.950 | 0.941 | 0.94% | 0.942 | 0.84% |
| **C3** | 0.982 | 0.971 | 1.10% | 0.997 | -1.53% |
| **C4** | 0.976 | 0.971 | 0.52% | 0.993 | -1.74% |
| **C5** | 0.977 | 0.967 | 1.03% | 0.974 | 0.31% |
| **C6** | 0.964 | 0.961 | 0.33% | 0.961 | 0.31% |
| **P1** | 0.960 | 0.944 | 1.63% | 0.952 | 0.83% |
| **P2** | 0.982 | 0.970 | 1.20% | 1.036 | -5.50% |
| **P3** | 0.949 | 0.948 | 0.08% | 0.954 | -0.53% |
| **P4** | 0.973 | 0.965 | 0.78% | 0.970 | 0.31% |
| **P5** | 0.984 | 0.990 | -0.65% | 1.048 | -6.50% |
| **P6** | 0.982 | 0.966 | 1.61% | 0.979 | 0.31% |
| **I1** | 0.974 | 0.972 | 0.20% | 0.973 | 0.10% |
| **I2** | 0.976 | 0.973 | 0.34% | 0.974 | 0.20% |
| **I3** | 0.969 | 0.966 | 0.34% | 0.995 | -2.68% |
| **I4** | 0.962 | 0.950 | 1.28% | 0.956 | 0.62% |
| **I5** | 0.982 | 0.972 | 0.98% | 1.032 | -5.09% |
| **I6** | 0.986 | 0.973 | 1.28% | 0.982 | 0.41% |

### Modeling Data

Table 23. Cable Type Impedances.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Cable Type** | **R1 (Ω/km)** | **X1 (Ω/km)** | **R0 (Ω/km)** | **X0 (Ω/km)** |
| **15kV Shielded 4/0 AWG 3C CU** | 0.1668 | 0.1286 | 1.3302 | 0.9830 |
| **15kV Shielded 500KCMIL SR 3C CU** | 0.0749 | 0.1167 | 1.1405 | 0.7559 |

Table 24. Line Segment Data.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Line** | **From (#Bus)** | **To**  **(#Bus)** | **Cable Type** | **Length**  **ft (km)** | **Line** | **From (#Bus)** | **To**  **(#Bus)** | **Cable Type** | **Length**  **ft (km)** |
| **C101** | #101 | #102 | 500 kcmil | 1800 (0.549) | **C201** | #201 | #204 | 4/0 AWG | 5500 (1.676) |
| **C102** | #101 | #105 | 500 kcmil | 5500 (1.676) | **C202** | #201 | #203 | 500 kcmil | 2000 (0.610) |
| **C103** | #101 | #103 | 4/0 AWG | 1000 (0.305) | **C203** | #201 | #208 | 500 kcmil | 3000 (0.914) |
| **C104** | #101 | #T107 | 500 kcmil | 3000 (0.914) | **C204** | #210 | #303 | 500 kcmil | 1500 (0.457) |
| **C105** | #105 | #204 | 500 kcmil | 3000 (0.914) | **C205** | #209 | #304 | 500 kcmil | 1500 (0.457) |
| **C106** | #105 | #106 | 500 kcmil | 1500 (0.457) | **C206** | #207 | #305 | 500 kcmil | 1500 (0.457) |
| **C107** | #106 | #205 | 500 kcmil | 2000 (0.610) | **C301** | #301 | #302 | 500 kcmil | 2500 (0.762) |
| **C108** | #104 | #206 | 500 kcmil | 1000 (0.305) | **C302** | #301 | #306 | 4/0 AWG | 2000 (0.610) |
| **C109** | #T107 | #307 | 500 kcmil | 2000 (0.610) | **C303** | #301 | #307 | 500 kcmil | 2000 (0.610) |
|  |  |  |  |  | **C304** | #301 | #305 | 4/0 AWG | 1500 (0.457) |

Table 25. Load Data.

| **Classification** | **ID** | **Connection** | **Demand**  **kVA** | **Classification** | **ID** | **Connection** | **Demand**  **kVA** |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Critical** | **C1** | #104 | 1200 | **Critical** | **C4** | #209 | 1000 |
| **C2** | #106 (T105) | 1500 | **C5** | #303 | 1000 |
| **C3** | #202 | 1000 | **C6** | #306 (T304) | 800 |
| **Priority** | **P1** | #107 | 1000 | **Priority** | **P4** | #305 | 600 |
| **P2** | #206 | 1000 | **P5** | #210 | 700 |
| **P3** | #205 (T205) | 1000 | **P6** | #307 | 1000 |
| **Interruptible** | **I1** | #102 (T101) | 300 | **Interruptible** | **I4** | #205 (T204) | 600 |
| **I2** | #105 (T106) | 250 | **I5** | #207 | 400 |
| **I3** | #204 (T202) | 300 | **I6** | #304 | 600 |

Table 26. Transformers Data.

| **ID** | **Nameplate** | | | | | **Computed** | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Rating**  **[kVA]** | **Vpri**  **[kV]** | **Vsec**  **[kV]** | **Z**  **[%]** | **X/R** | **X**  **[%]** | **R**  **[%]** |
| **T101** | 500 | 13.8 | 0.48 | 5.00 | 4.9 | 4.90 | 1.00 |
| **T102** | 2500 | 13.8 | 0.48 | 5.75 | 6.6 | 5.69 | 0.86 |
| **T103** | 3750 | 13.8 | 4.16 | 4.75 | 11.4 | 4.73 | 0.42 |
| **T104** | 2000 | 4.16 | 0.48 | 5.75 | 4.7 | 5.62 | 1.20 |
| **T105** | 2000 | 4.16 | 0.48 | 5.75 | 4.7 | 5.62 | 1.20 |
| **T106** | 500 | 13.8 | 0.208 | 5.00 | 4.9 | 4.90 | 1.00 |
| **T107** | 2500 | 13.8 | 0.48 | 5.75 | 6.6 | 5.69 | 0.86 |
| **T201** | 2500 | 13.8 | 0.48 | 5.56 | 5.5 | 5.47 | 0.99 |
| **T202** | 500 | 13.8 | 0.208 | 5.00 | 4.9 | 4.90 | 1.00 |
| **T203** | 3750 | 13.8 | 4.16 | 4.75 | 11.4 | 4.73 | 0.42 |
| **T204** | 1000 | 4.16 | 0.48 | 5.75 | 4.2 | 5.59 | 1.33 |
| **T205** | 1500 | 4.16 | 0.48 | 5.75 | 5.0 | 5.64 | 1.12 |
| **T206** | 2500 | 13.8 | 0.48 | 5.75 | 6.6 | 5.69 | 0.86 |
| **T207** | 5000 | 13.8 | 0.48 | 5.00 | 5.4 | 4.92 | 0.90 |
| **T208** | 2000 | 13.8 | 0.48 | 5.75 | 4.7 | 5.62 | 1.20 |
| **T209** | 2000 | 13.8 | 0.48 | 5.75 | 4.7 | 5.62 | 1.20 |
| **T210** | 1000 | 13.8 | 0.48 | 5.75 | 4.2 | 5.59 | 1.33 |
| **T301** | 2000 | 13.8 | 0.48 | 5.75 | 4.7 | 5.62 | 1.20 |
| **T302** | 2000 | 13.8 | 0.48 | 5.75 | 4.7 | 5.62 | 1.20 |
| **T303** | 1000 | 13.8 | 0.48 | 5.75 | 4.2 | 5.59 | 1.33 |
| **T304** | 1000 | 13.8 | 0.48 | 5.75 | 4.2 | 5.59 | 1.33 |
| **T305** | 2500 | 13.8 | 0.48 | 5.75 | 6.6 | 5.69 | 0.86 |

### References

[3] – Banshee distribution network benchmark and prototyping platform for hardware-in-the-loop integration of microgrid and device controllers. The Journal of Engineering, 2019: 5365-5373. https://doi.org/10.1049/joe.2018.5174

[4] – Electric Power Hardware-in-the-loop Controls Collaborative. Available at https://github.com/PowerSystemsHIL/EPHCC/releases/download/BansheeBenchmark/Supporting.Data.for.Banshee.Benchmark.Paper.zip