Understanding line losses and transformer losses in rural isolated distribution systems

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Photo by Dennis Schroeder, NREL 55200

Contents

Energy Systems Integration Facility

- The Energy Systems Integration Facility (ESIF) is a national User Facility located in Golden, Colorado on the campus of the National Renewable Energy Laboratory (NREL).

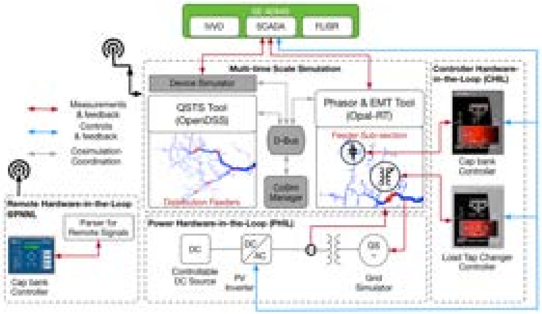
http://www.nrel.gov/esif

Photos by NREL

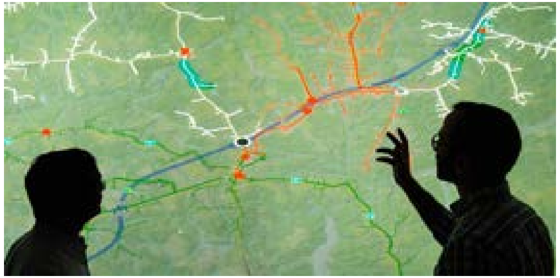
Controller and Power Hardware In The Loop (CHIL/PHIL)

- NREL's megawatt-scale controller and power hardware-in-the-loop (CHIL/PHIL) capability allows researchers and manufacturers to test energy technologies at full power in real-time grid simulations to safely evaluate performance and reliability.

Microgrids



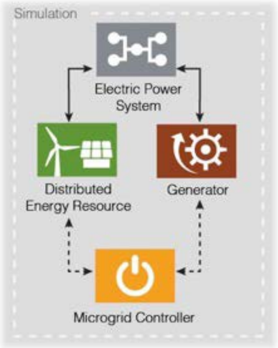
Cosimulation



Power System Studies

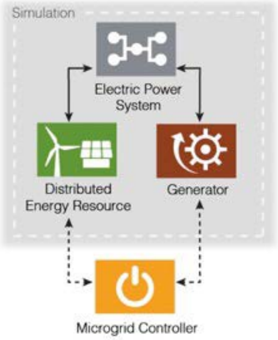
Hardware-in-the-loop

A) Pure simulation



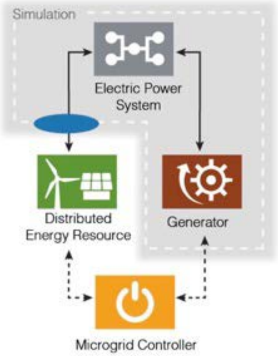
A) Pure Simulation

B) Controller-hardware-in-the-loop



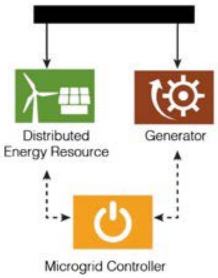
B) CHIL

C) Controller-hardware-in-the-loop and power-hardware-in-the-loop



C) CHIL & PHIL

D) Hardware only

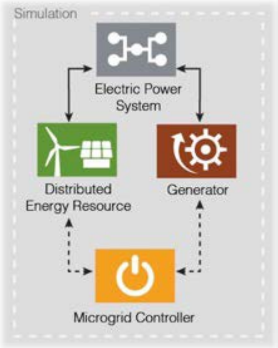


D) Hardware only

Source: Maitra 2007

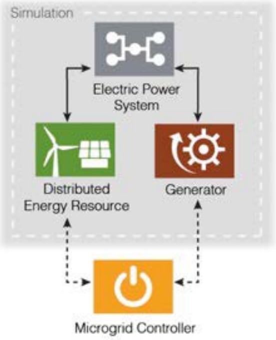
Hardware-in-the-loop

A) Pure simulation



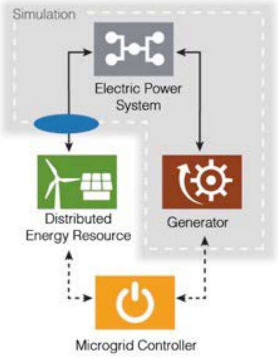
A) Pure Simulation

B) Controller-hardware-in-the-loop



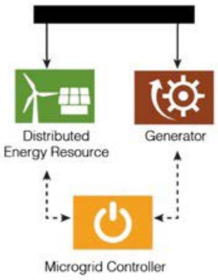
B) CHIL

C) Controller-hardware-in-the-loop and power-hardware-in-the-loop



C) CHIL & PHIL

D) Hardware only



D) Hardware only

Source: Maitra 2007

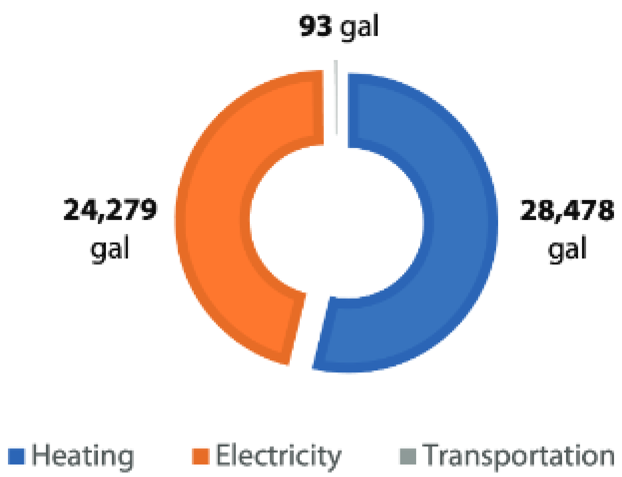
Community Background

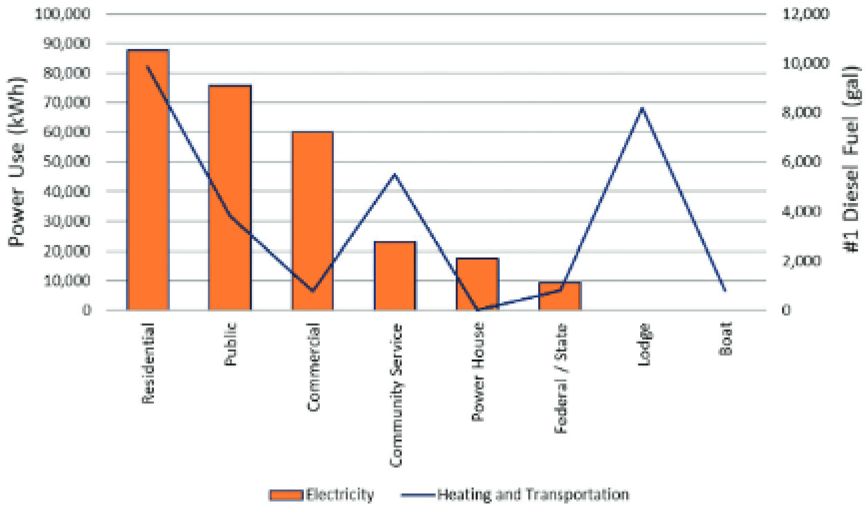
Photo by Levi Kilcher, NREL

Background on Igiugig power system

- Igiugig, Alaska. Located South west of Anchorage.
- 12 kV system with peak loads approximately lower than 100 kW.
- Primarily supported by diesel generators.
- High diesel cost.

Background on Igiugig power system





2019 diesel fuel usage for electricity and heat, in total and by premise type

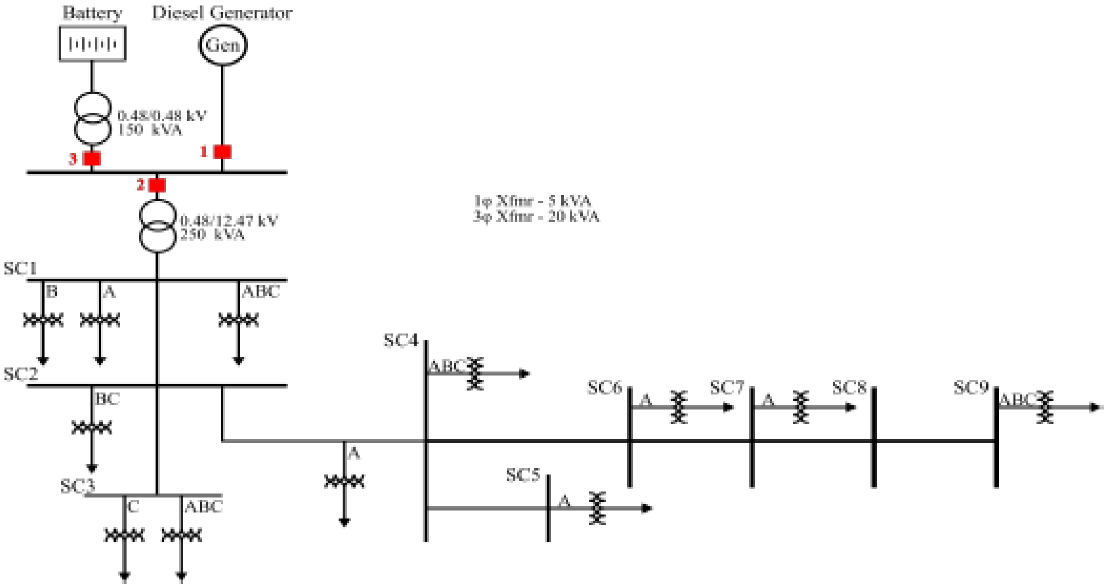
- Addressing losses in the power system can be crucial in saving diesel consumption.

Source: Salmon 2022

Background on losses

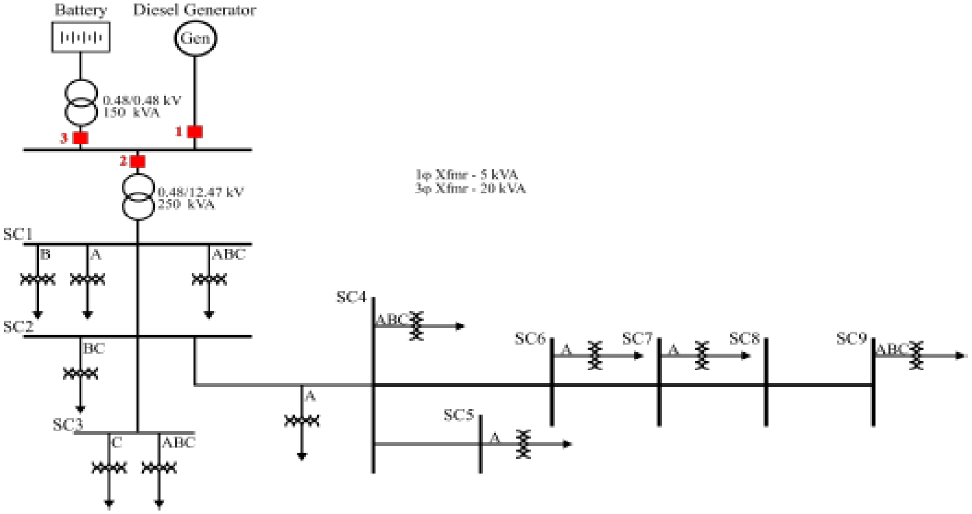
- Well understood phenomenon.
- Primarily from lines, transformers (no load and on-load losses).
- Currently, a lack of information in open source to address this for the isolated microgrids, and small island power systems.
- We aim to address this by leveraging best modeling practices and using electromagnetic transient domain (EMT) simulation.

Network structure



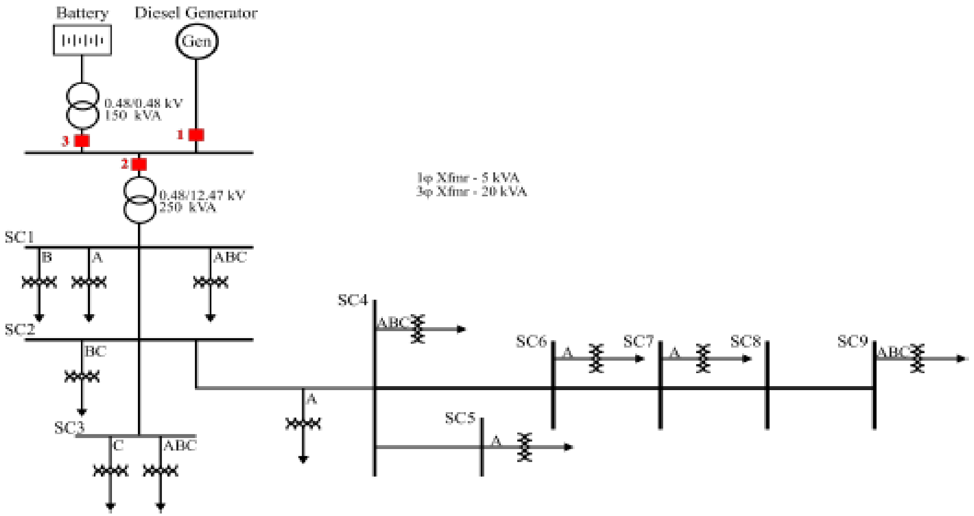
- Radial in nature.
- Underground cable infrastructure to distribute power.
- Inductors used to compensate for reactive power contribution from underground cables.

Underground cables



- #2 AWG Aluminum, 15 kV, EPR insulation at 133%
- Conductor resistance - 0.8715 Ω/km
- Cable Capacitance – 0.157 μF/km
- Positive sequence impedance – 1.19 Ω/km
- Zero sequence impedance – 2.5 Ω/km
- Zero sequence to positive sequence ratio – 2.1 (assumed)

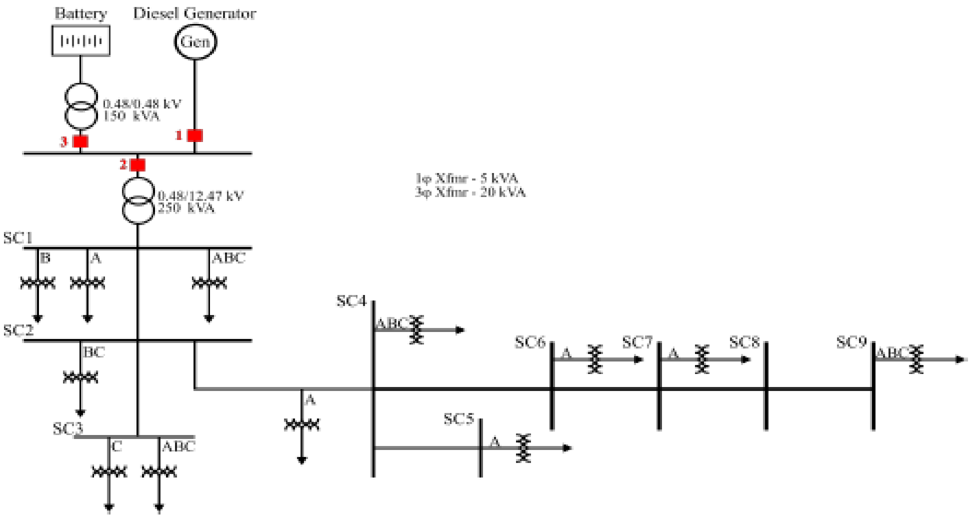
Underground cables



- Conductor resistance - 0.5518 Ω/km (calculated)
- Cable Capacitance – 0.12 μF/km (assumed)
- Positive sequence impedance – 0.56 Ω/km (calculated)
- Zero sequence impedance – 1.176 Ω/km (calculated)
- Zero sequence to positive sequence ratio – 2.1 (assumed)

Stock Number	Code Word	Phase Cond. Size	DC Resistance @ 25°C	AC Resistance @ 90°C	Inductive Reactance @ 60Hz	GMR	Allowable Ampacity in Duct 90°C	Allowable Ampacity Directly Buried 90°C
		AWG/Kcmil	Ω/1000ft	Ω/1000ft	Ω/1000ft	ft	Amp	Amp
378182	Converse	2/0	0.1312	0.1682	0.0308	0.0121	150	150

Transformers



- Three large transformers
- Multiple distribution transformers
  - 15 kVA 2.2% impedance
  - 12.47 kV/7.2kV to 240V/120V

Transformers

Main Xfmr

General	
Transformer Name	TGen1
3 Phase Transformer MVA	0.2 [MVA]
Base Operation Frequency	60.0 [Hz]
Winding #1 Type	Y
Winding #2 Type	Y
Delta Lags or Leads Y	Lags
Positive Sequence Leakage Reactance	0.035 [pu]
Ideal Transformer Model	No
Eddy Current Losses	0.02 [pu]
Copper Losses	0.03 [pu]
Tap Changer on Winding	None
Graphics Display	Single line (circles)
Display Details?	No

1 phase Xfmr

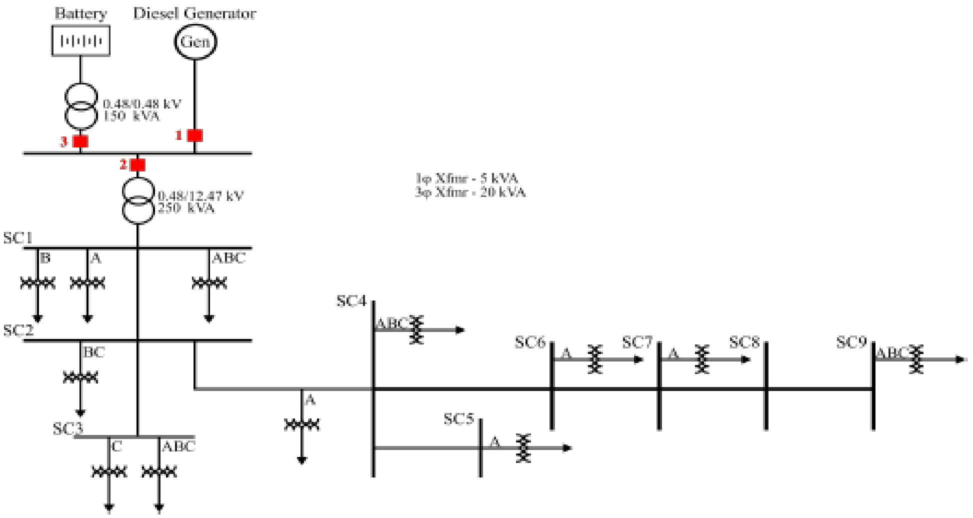
General	
Name for Identification	
Transformer MVA	0.005 [MVA]
Base Operation Frequency	60.0 [Hz]
Leakage Reactance	0.035 [pu]
Eddy Current Core Loss	0.02 [pu]
Copper Losses	0.03 [pu]
Ideal Transformer Model	No
Tap Changer on Winding	None
Graphics Display	Windings
Winding Voltages	
Winding #1 Voltage (RMS)	7.2 [kV]
Winding #2 Voltage (RMS)	0.120 [kV]

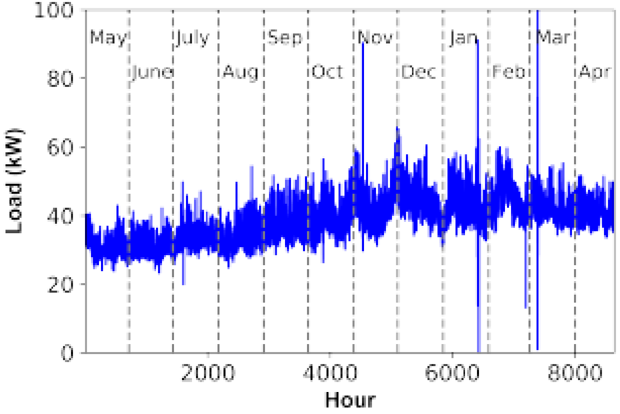
3 phase Xfmr

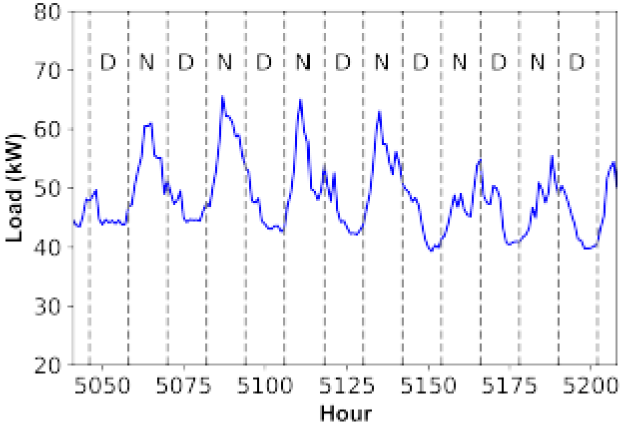
General	
Transformer Name	TGen1
3 Phase Transformer MVA	0.02 [MVA]
Base Operation Frequency	60.0 [Hz]
Winding #1 Type	Delta
Winding #2 Type	Y
Delta Lags or Leads Y	Lags
Positive Sequence Leakage Reactance	0.039 [pu]
Ideal Transformer Model	Yes
Eddy Current Losses	0.02 [pu]
Copper Losses	0.03 [pu]
Tap Changer on Winding	None
Graphics Display	Single line (circles)
Display Details?	No

- No load losses are assumed to be 2%
- Copper losses are assumed to be 3%
- All single phase transformers are rated at 5 kVA
- Three phase transformers are rated at 20 kVA

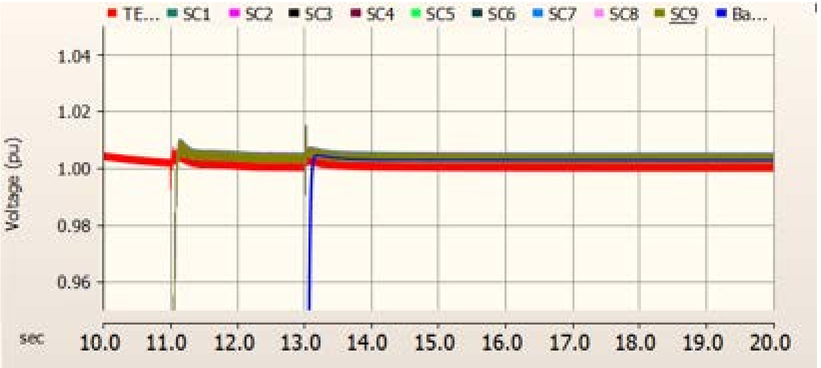
Load profile



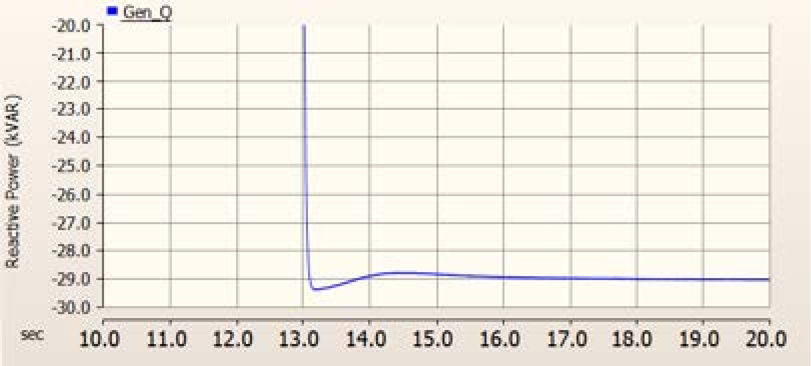




Full load

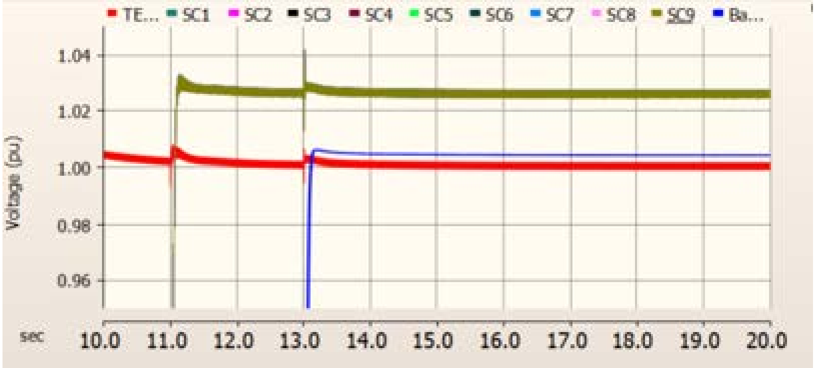

TE... SC1 SC2 SC3 SC4 SC5 SC6 SC7 SC8 SC9 Ba...
Voltage (pu)
1.04
1.02
1.00
0.98
0.96
sec
10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0

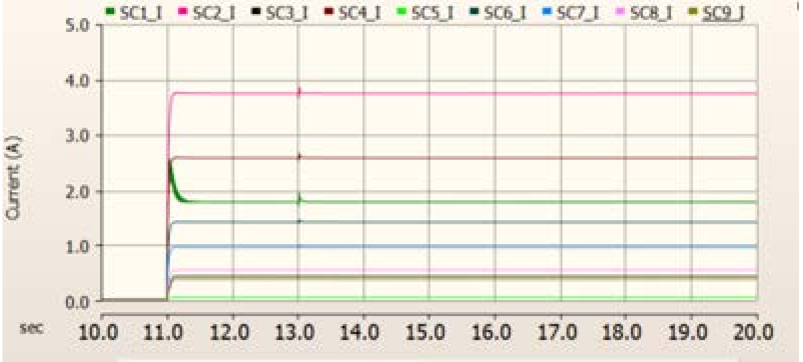

SC1_I SC2_I SC3_I SC4_I SC5_I SC6_I SC7_I SC8_I SC9_I
Current (A)
5.0
4.0
3.0
2.0
1.0
0.0
sec
10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0


Gen_Q
Reactive Power (kVAR)
-20.0
-21.0
-22.0
-23.0
-24.0
-25.0
-26.0
-27.0
-28.0
-29.0
-30.0
sec
10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0

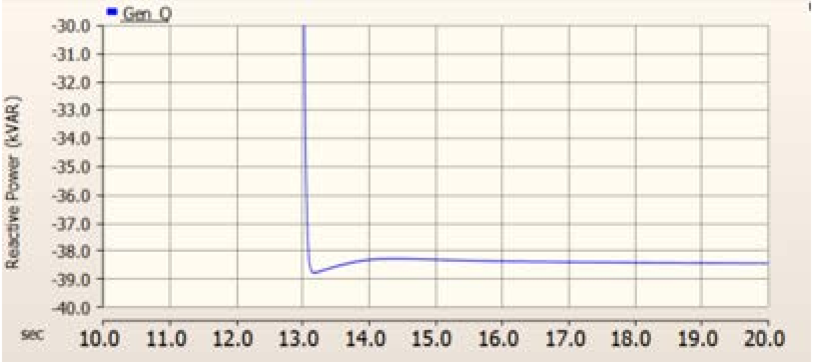

Gen_P
Real Power (kW)
70.0
69.0
68.0
67.0
66.0
65.0
sec
10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0

Half load


TE... SC1 SC2 SC3 SC4 SC5 SC6 SC7 SC8 SC9 Ba...
Voltage (pu)
1.04
1.02
1.00
0.98
0.96
sec
10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0


SC1_I SC2_I SC3_I SC4_I SC5_I SC6_I SC7_I SC8_I SC9_I
Current (A)
5.0
4.0
3.0
2.0
1.0
0.0
sec
10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0


Gen_P
Real Power (kW)
40.00
39.75
39.50
39.25
39.00
38.75
38.50
38.25
38.00
sec
10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0


Gen_Q
Reactive Power (kVAR)
-30.0
-31.0
-32.0
-33.0
-34.0
-35.0
-36.0
-37.0
-38.0
-39.0
-40.0
sec
10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0

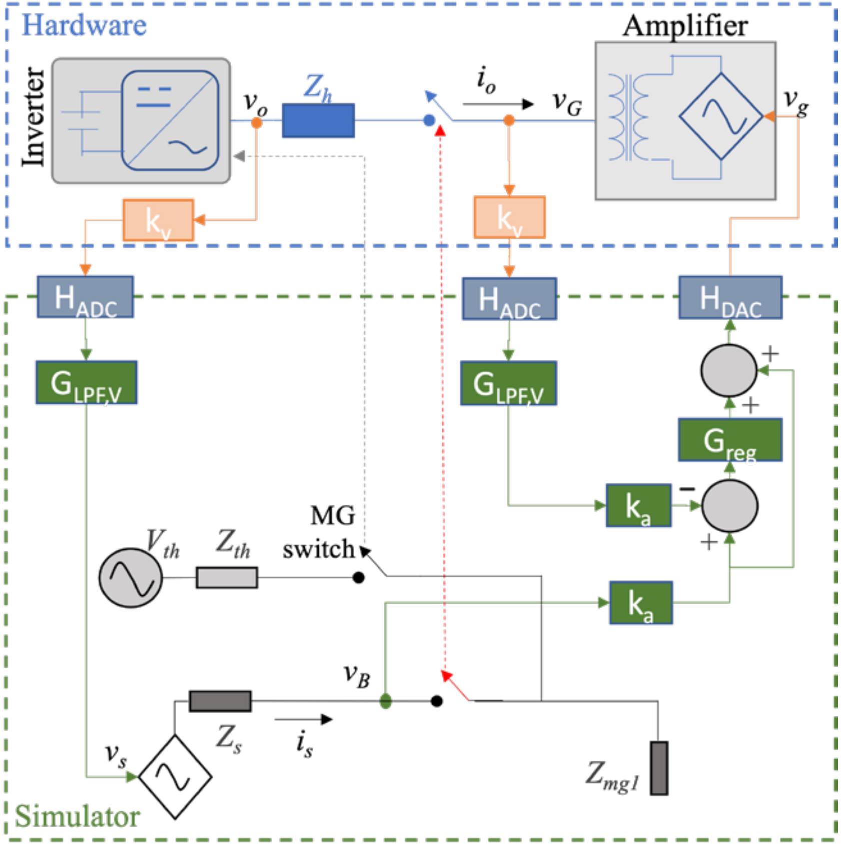
10 percent load

Network loss summary

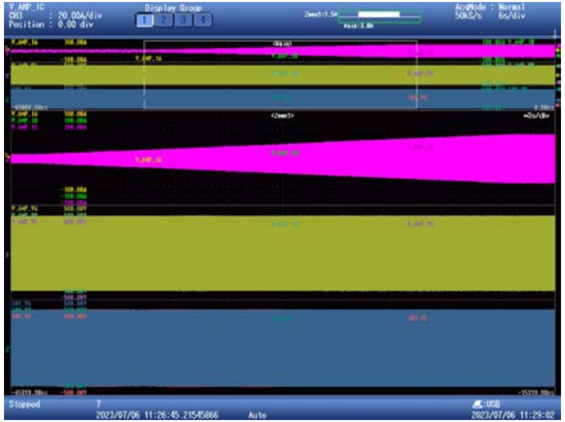
Scenario	Load		Generation		Losses (kW)
	P (kW)	Q (kVAR)	P (kW)	Q (kVAR)	
1 (Full load)	61	6	68.5	-29	7.5
2 (50% load)	30.5	3.05	39.5	-38.5	9
3 (10% load)	6.0	0.6	14.3	-44	8.1

- Loss values are as expected and primarily from transformers.
- Why is this important?
- How to compensate or reduce these loses?

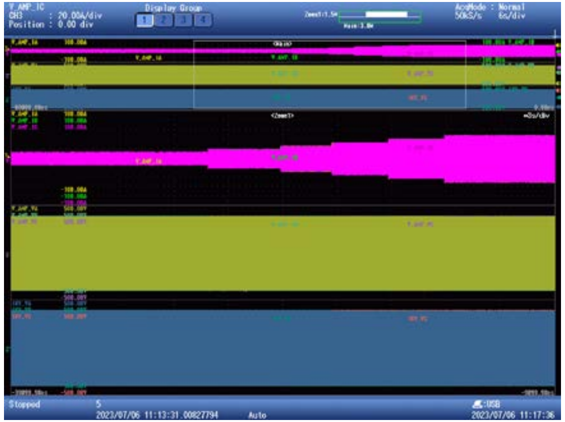
Future work



Source: Pratt 2023



Scope capture of the inverter dispatch change in grid-connected operation showing the (top) current, (middle) the amplifier voltage, and (bottom) inverter voltage.



Scope capture of the load step change in islanded operation showing the (top) current, (middle) the amplifier voltage, and (bottom) inverter voltage.

Summary

- Losses in distribution system are not new. Well known and well studied.
- But, they are still a key challenge for isolated microgrid systems and island power systems.
- Understanding line losses and addressing line losses are critical for communities that are primarily using diesel generators.
- This work aims to support community efforts to address losses in the system.
- We are recommending building key EMT models to answer loss related questions and pave way for future grid integration questions.

References

Maitra, Arindam, Annabelle Pratt, Tanguy Hubert, Dean Wang, Kumaraguru Prabakar, Rachna Handa, Murali Baggu, and Mark McGranaghan. 2017. "Microgrid Controllers: Expanding Their Role and Evaluating Their Performance." *IEEE Power and Energy Magazine*. https://doi.org/10.1109/MPE.2017.2690519.

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A. Pratt, K. Prabakar, S. Ganguly and S. Tiwari, "Power-Hardware-in-the-Loop Interfaces for Inverter-Based Microgrid Experiments Including Transitions," 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023, pp. 537-544, doi: 10.1109/ECCE53617.2023.10362806.

Thank you

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