Understanding Line Losses and Transformer Losses in Rural Isolated Distribution Systems

Preprint

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To be presented at the 2024 IEEE Rural Electric Power Conference
Tulsa, Oklahoma
April 30–May 2, 2024

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-88937
March 2024

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Suggested Citation
Prabakar, Kumaraguru, Yaswanth Nag Velaga, Rebecca Meadows, Ben McGilton, Tessa Greco, Jonathan Salmon, Karl Hill, and Levi Tinney. 2024. *Understanding Line Losses and Transformer Losses in Rural Isolated Distribution Systems: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-88937. https://www.nrel.gov/docs/fy24osti/88937.pdf.

Contract No. DE-AC36-08GO28308

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NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Energy Transitions Initiative, Building Technologies Office, Geothermal Technologies Office, Solar Energy Technologies Office, Vehicle Technologies Office, Water Power Technologies Office, and Wind Energy Technologies Office.

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Understanding line losses and transformer losses in rural isolated distribution systems

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***Abstract*—Rural, isolated power systems in the mainland United States and in states like Alaska and Hawaii are powered by assets like diesel generators. These rural, isolated power systems cannot operate at the higher band of medium voltage (like 69 kV). They primarily operate in the 12–14 kV range to keep the cost of the distribution investments lower. Because of this mid-band medium-voltage range, the diesel consumption from line losses and distribution transformer losses is significant (almost 10% of the peak load). This work considers one such isolated power system and presents key findings about online losses and transformer losses. Understanding and documenting the impacts from losses is critical for communities that operate these power systems so they can take actions to reduce expensive diesel consumption. In this paper, we will present one such typical grid and model it in the electromagnetic transients domain. We used the tower structure and underground cabling installation to develop high-fidelity models of the lines. We also used high-fidelity models of distribution transformers to present the no-load losses and full-load losses. We present technical solutions that are available commercially off-the-shelf to reduce losses and reduce diesel consumption. This work will be a primer for communities to understand the technical challenges and possible solutions for rural, isolated power system operators.**

I. INTRODUCTION

Rural isolated power systems are grids that support smaller villages and cities in isolated locations. These can be power systems supporting cities with 100s of residents to 1000s of residents. In the past, these power systems were powered by diesel generators, gas turbines, and in some cases hydro plants [1]. Recent developments in inverter based assets, energy storage assets, and distributed energy resource management systems has created opportunities for these isolated power systems and challenges in real time operation of these systems. A key consideration for remote rural isolated power system powered by diesel generators is the dependence on diesel supply chain [2]. This dependency can make the electricity cost expensive. In addition, any disruption in diesel supply chain during extreme weather conditions can create brown outs/black outs which can create losses for the community.

The system at study reflects a typical isolated power system in rural Alaska. The system considered here is in Igiugig, Alaska. The location of the power system is shown in Fig. 1. It is powered mainly by diesel generators [3], and diesel is typically flown in or brought in over water on barges. During extreme weather conditions, access to diesel can be limited and the cost can be high—this creates challenges for operating rural electric power systems. The rural power system in consideration contains primarily underground cabling for distribution, and uses distribution transformers for stepping down the voltage. Currently, one of the main challenges is to identify and understand the losses in the power system [4]. Understanding these losses will allow for better planning of renewable distributed energy resources and optimal location of the assets to support better voltage profile and minimize losses. The report presented in [4] also identifies that for future capacity development independence, predictable budgeting and training are critical.

Fig. 1. Location of Igiugig, Alaska, power system in reference to Anchorage, Alaska

In this paper, we aim to develop a high fidelity electromagnetic transient (EMT) model of the rural power system. The model was developed with the network structure reflecting the under ground cabling infrastructure, distribution transformers, and the diesel generators. Using the approach, we are able to understand the losses in the network and the need for compensating the losses to reduce diesel consumption in the system. In addition to this, we are able to use the EMT model to be converted to an EMT model that can run in a digital real time simulator. This also allows the community to reuse the model to evaluate future distributed energy resource management systems and train system operators. We have also presented the abstract approach in the paper for other communities to reuse [5].

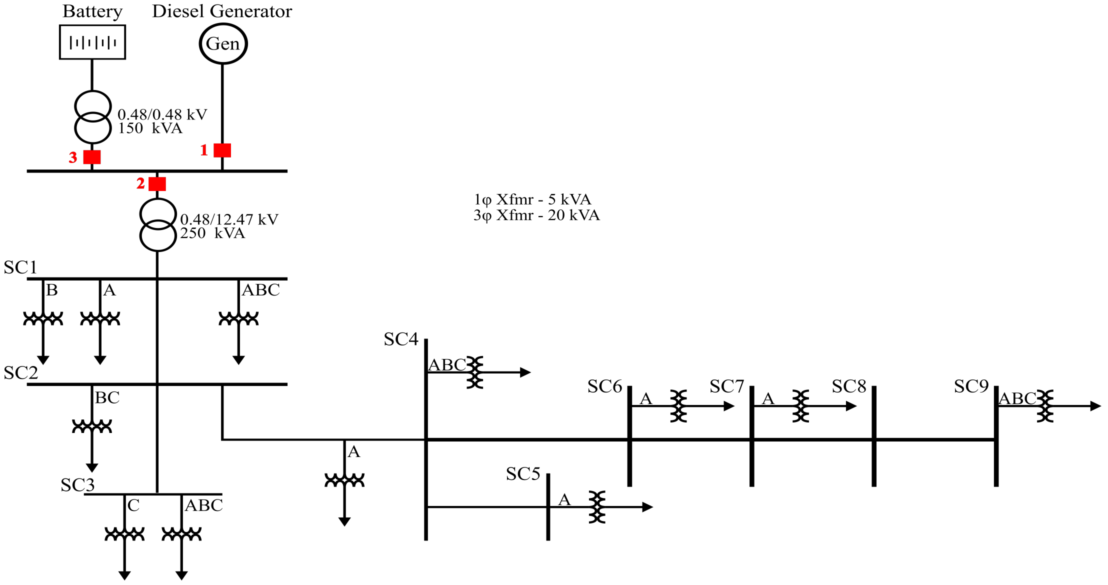


Fig. 2. One line diagram of Igiugig network

II. BACKGROUND ON NETOWRK LOSSES

In a standard distribution system, the following items can contribute to system losses [6]: 1. Line losses on phase conductors, 2. transformer core losses and leakage losses In other cases, load imbalances and lack of reactive power coordination can cause additional losses. In the system under study, smart meter readings at the generating asset and at the loads indicate losses of around 15% [4]. This number has been increasing due to load growth and possibly due to other power quality challenges. In the system under study, distribution transformers are used near the load to step down the voltage from 12 kV to 208 V or 120 V.

A. Power losses in transformers:

Core loss (no-load loss) and copper loss (load loss) contribute to power losses in distribution system transformers. The no-load loss is primarily due to core loss, and a negligible dielectric loss. The full-load loss is the I^2R loss in the windings of the transformer and the eddy-current loss due to circulating eddy currents in the transformer core. These losses are dependent on model type and can be obtained from manufacturer nameplate. In the system, all the distribution transformers are primarily one model type.

B. Use of distributed generation to support losses:

In literature, many papers have discussed the use of distributed generation to support losses [7]. The general consensus is that a distributed generation like PV will improve voltage profile, reduce losses and support some of the power lost in the system. In the system under study, the generation assets are located at one bus which includes the diesel generator and battery energy storage system (currently being planned for operation). In our work, we modeled the system in EMT to create a baseline for loss characterization. This will allow the community to strategically invest in distributed energy resources to compensate for the losses in the system.

TABLE I
UNDERGROUND CABLE DATA

Specification	12 kV	480 208 120 V
Conductor Size	2 AWG	2 AWG
Conductor Resistance	0.8715 Ω/km	0.5518 Ω/km
Capacitance	0.157 μ/km	0.12 μ/km
Positive Sequence Impedance	1.19 Ω/km	0.56 Ω/km
Zero Sequence Impedance	2.5 Ω/km	1.176 Ω/km

III. POWER SYSTEM MODEL

The model consists of three generator assets and represented as one grid at rated voltage shown in Fig. 2. Table I shows the cable data for 12 kV and 480, 208, 120 V cables. These parameters are used to model lines in the network using the pi model. Impedance parameters are converted from ohms per kilometer to ohms per meter. High-voltage cables (12 kV) connecting the switchgears and step-down transformers are assumed to be 1 km in length, except for the cable connecting SC2-SC3, which was assumed to be 1.5 km in length. Low-voltage cables from step-down transformers to loads are assumed to be 0.1 km in length.

The Network under study has several transformers for stepping up and down from generation to the load. Three-phase, two-winding and single-phase, single-winding transformers are modeled per the rating in the one line diagram (as shown in Fig. 2). Reactance and losses (eddy current, copper) are assumed to be 0.035 pu, 0.05 pu, and 0.1 pu.

Loads are represented using constant impedance model. Active and reactive power ratings of each load are assumed values. Based on field measurement data, load ratings will be corrected and updated in the model.

TABLE II
EXISTING ENERGY RESOURCES IN THE IGIUGIG SYSTEM

Type	Rating	Grid-forming or grid-following
Diesel generators (three in number)	65 kW	Grid-forming and grid parallel
Battery Energy Storage system	250-kWh 125-kW	Grid-forming and grid-following
River generator (two in number)	40 kW	Grid-following

A. Network model

The network topology for the Igiugig system is primarily radial. The diesel generators and the battery energy storage system are at the top of the feeder system. The river generator is approximately located at the middle of the feeder. The additional planned solar photovoltaic system will be at the end of the system (SC9). The system is primarily underground cable distributed and is a good test distribution feeder for the systems contiguous United States that are being converted from overhead lines to underground cables to reduce wildfire-related risks. For the purposes of the loss calculation, we only dispatch the diesel generators. The Battery energy storage system and the river generators are not dispatched.

B. Energy resources

Currently, there are three diesel generators, two river generators, and one battery energy storage system. The ratings and capabilities of the generation systems in the field are presented in Table II. The diesel generators are the primary source of generation. In PSCAD, one aggregated generator model of 90 kW is modeled because diesel generators are not expected to supply more than 90 kW during peak load conditions. Various forms of renewable energy sources are being planned to reduce the dependence on diesel. Due to the atmospheric conditions in Alaska, the generation contribution from solar and river energy sources is limited to the summer season. To optimize the available resources and identify the high losses, the Igiugig network model is developed in PSCAD.

C. Cable model

The underground cable model is developed based on the assumed data in Table I. All the cables between switchgears and from switchgear to transformer are modeled using PI lines. All the impedance parameters in the PI model are modeled based on Table I.

D. Load models

Most of the loads in the Igiugig system are building loads. There are a few machine loads that are utilized for the water distribution system. These are considered small motor loads compared to the asset sizing, so they do not create major transient challenges during start-up. The majority of the loads are refrigeration, space heating, and lighting. Figure. 3 shows the hourly load for one year, from May to April. Figure. 4 & 5 shows the weekly load obtained from the yearly load during high and medium peaks. These figures show that peak load is greater in night (N) compared to day(D). During the summer months, average load of the network is around 30 kW. The load gradually increases to a peak of 60 kW during winter, except for a few peaks of 100 kW. These peaks are caused during BESS testing which demanded current to charge. Since the load details of each customer are not available, load numbers are assumed based on the transformer ratings. Table III shows the load distribution at each transformer. The total assumed three-phase load is 61 kW and 6.1 kVAR. For the purposes of this paper, we have modeled the loads as constant impedance loads.

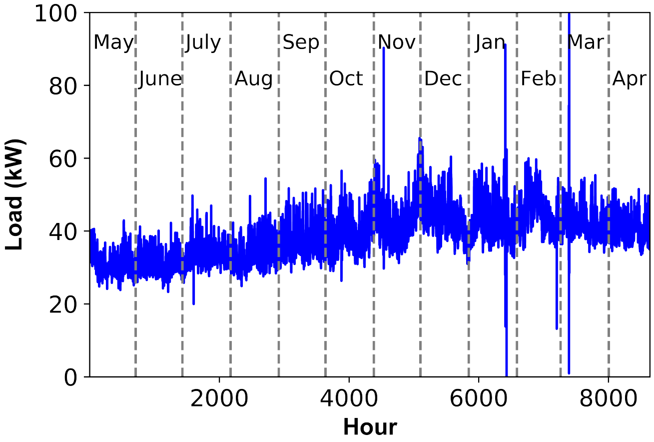


Fig. 3. Total Igiugig hourly load for one year

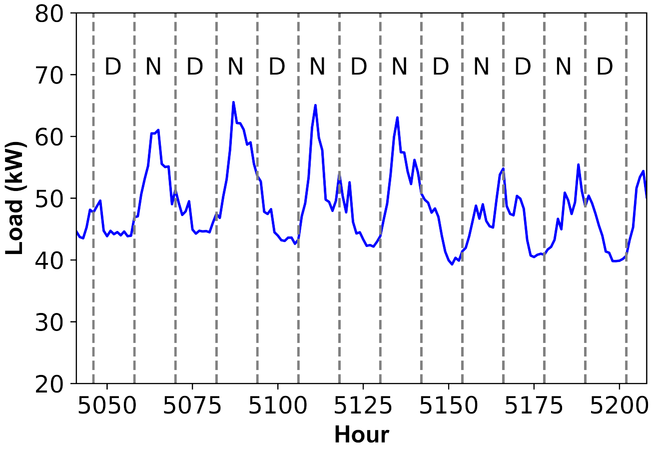


Fig. 4. Zoomed in view of hourly load during a week with high peaks (peaks occurring during night time)

IV. SIMULATION SCENARIOS AND RESULTS

EMT programs were widely used in determining the component ratings such as insulation levels and energy absorption capabilities. Due to the high deployment of inverter-based resources (IBRs), EMT platforms are used to model IBRs in detail and study their impact on the distribution systems. EMT simulation tools can be classified into offline and real-time tools. Offline simulation tools are used to conduct simulations

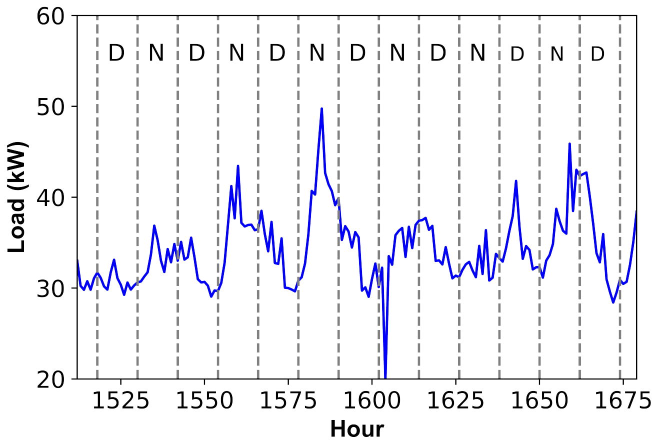


Fig. 5. Zoomed in view of hourly load during a week with medium peaks (peaks occurring during night time)

TABLE III
SYSTEM LOAD DISTRIBUTION AT THE DIFFERENT SWITCH GEARS

	Load real power (kW)			Load reactive power (kVAR)		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
SC1	0.5	0.5	0.5	0.05	0.05	0.05
	5	0	0	0.5	0	0
	0	5	0	0	0.5	0
SC2	0	0.5	0.5	0	0.05	0.05
	0.5	0	0	0.05	0	0
SC3	5	5	5	0.5	0.5	0.5
	0	0	1.5	0	0	0.15
SC4	5	5	5	0.5	0.5	0.5
SC5	0.5	0	0	0.05	0	0
SC6	0.5	0	0	0.05	0	0
SC7	0	0.5	0	0	0.05	0
SC9	5	5	5	0.5	0.5	0.5
Total load	22	21.5	17.5	2.2	2.15	1.75

on a computer, whereas digital real-time simulation tools are capable of running simulations in real time and can be interfaced with physical devices and generating results synchronous with the current time.

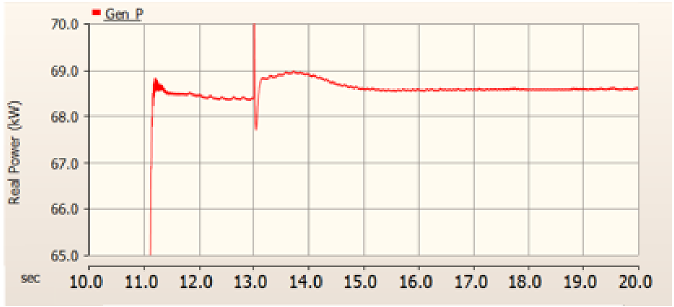
Iguigig network modeled in PSCAD is simulated under three loading scenarios (high, medium and low) to determine the losses in the network experienced by the system. This effort is critical for the system operator to understand the necessary transition steps needed to add renewable energy into the system.

A. Scenario 1: 100% load

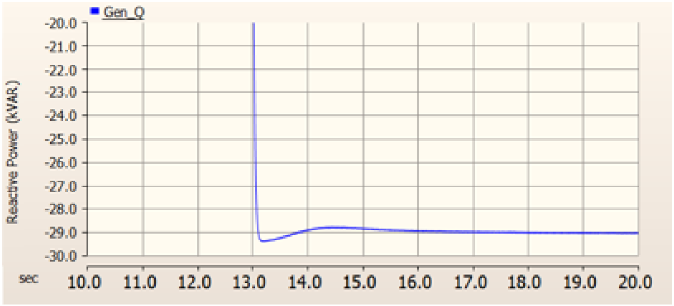
In this scenario, network is simulated at full load to determine the extent of losses in the network. Figure 6 shows the voltages, currents at different switchgear location and the diesel generator active and reactive power. Full network is connected in three steps: 1) diesel generator breaker 1 in fig. 2 is closed at 1 seconds, 2) Load network breaker 2 is closed at 11 seconds and 3) Battery storage system breaker 3 is closed at 13 seconds. Voltages in fig. 6 (a) show that all the switch gear locations are approximately 1 p.u. For full load of 61 kW and 6 kVAR, diesel generator supplies 68.5 kW and reactive power is absorbed due to the excess reactive power generated from underground cables. Total active power losses at full load is 11% (see table. IV).

(a) Switchgear Voltages

(b) Switchgear Currents

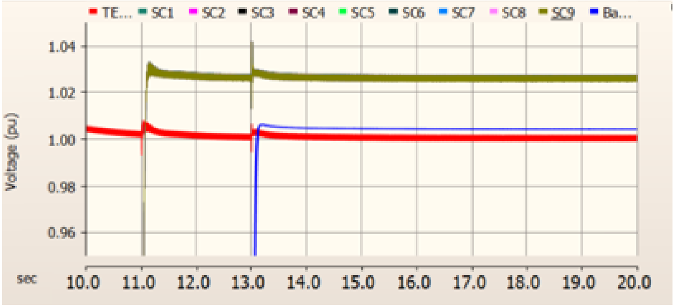


(c) Diesel Generator Active Power

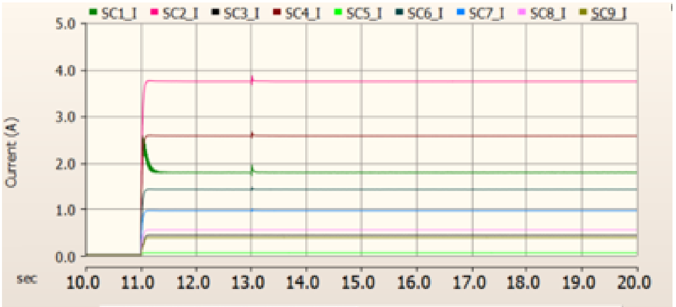


(d) Diesel Generator Reactive Power

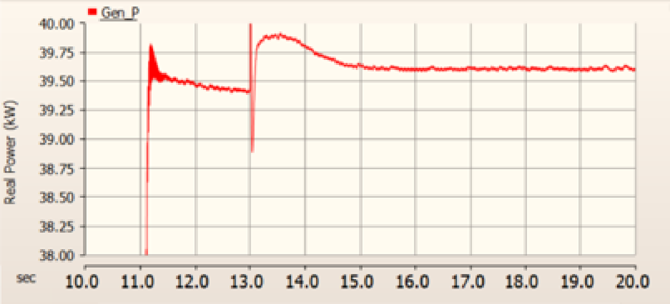
Fig. 6. Scenario 1: Network voltage, currents, diesel generator active and reactive power



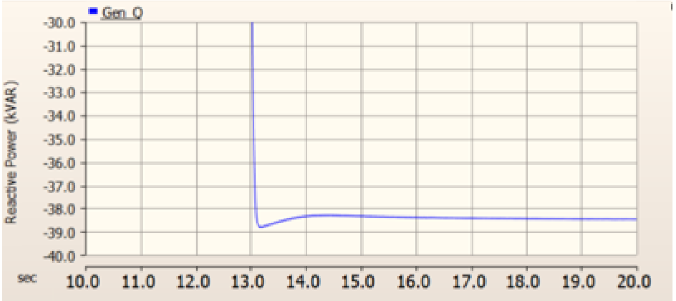
(a) Switchgear Voltages



(b) Switchgear Currents



(c) Diesel Generator Active Power



(d) Diesel Generator Reactive Power

Fig. 7. Scenario 2: Network voltage, currents, diesel generator active and reactive power

B. *Scenario 2: 50% load*

In this scenario, network is simulated at 50% of the load to determine the extent of line losses and compared to high and low scenarios. Figure 7 shows the voltages, currents at different switch gear location and the diesel generator active and reactive power. Figure. 7 (a) shows the voltages at the end of the network SC9 are greater than 1 p.u. This is due to the ferranti effect of underground cables. Even though diesel is absorbing excess reactive power, there are shunt reactors to absorb additional reactive power from underground cables. For 50% load, DG supplies 39.5 kW and reactive power is absorbed due to the excess reactive power generated from underground cables. In fact, reactive power absorption has increased due to less load compared to scenario 1. Total active power losses at full load is 23% (see table. I). Since the losses are increasing with decreasing load, it means that apart from line losses there is also a static loss from transformers.

C. *Scenario 3: 10% load*

In this scenario, network is simulated at 10% of the load to determine the extent of static losses. Figure 8 shows the voltages, currents at different switch gear location and the diesel generator active and reactive power. Figure. 7 (a) shows the voltages at the end of the network SC9 are approximately 1.4 p.u. This is due to the ferranti effect of underground cables. For 10% load, DG supplies 14.3 kW and reactive power is absorbed due to the excess reactive power generated from underground cables. In fact, reactive power absorption has further increased due to light load compared to scenario 2. Total active power losses at full load is 57% (see Table. IV). From scenario 1, 2, and 3 total losses has increased which means most of the losses are from transformers. This will be further validated with field measurements in the future publication.

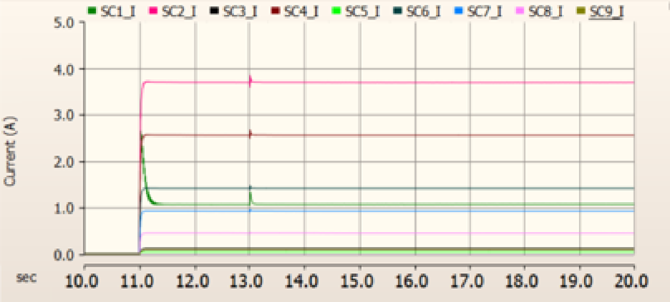
V. CONCLUSION

In this paper, we built a high-fidelity electromagnetic transient model for a rural isolated microgrid system. In this work, we used the model to understand line losses, transformer losses, and distributed energy resource integration into the system. For future controller hardware-in-the-loop experiments and power hardware-in-the-loop experiments, this model has the necessary information to be converted to real-time electromagnetic transients model. We showed the steps necessary to take a blueprint model of the system and build an electromagnetic transient model for a similar community to replicate this work. Communities with isolated power system can use the approach presented here to understand operational challenges of their respective power systems. The EMT model presented here will be updated in the future based on SCADA data to improve the accuracy of the model.

TABLE IV
NETWORK LOSS SUMMARY

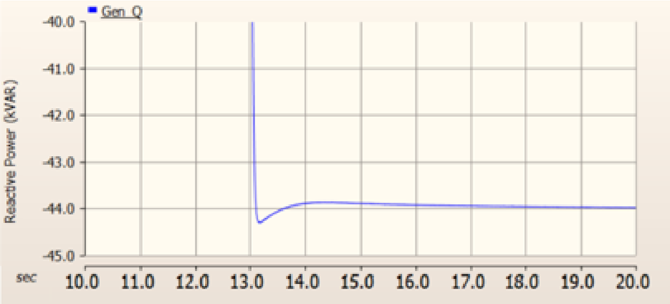
Scenario	Load		Generation		Losses (kW)
	P (kW)	Q (kVAR)	P (kW)	Q (kVAR)	
1 (Full load)	61	6	68.5	-29	7.5
2 (50% load)	30.5	3.05	39.5	-38.5	9
3 (10% load)	6.0	0.6	14.3	-44	8.1

(a) Switchgear Voltages



(b) Switchgear Currents

(c) Diesel Generator Active Power



(d) Diesel Generator Reactive Power

Fig. 8. Scenario 3: Network voltage, currents, DG active and reactive power

ACKNOWLEDGMENT

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by DOE Office of Energy Efficiency and Renewable Energy Energy Transitions Initiative, Building Technologies Office, Geothermal Technologies Office, Solar Energy Technologies Office, Vehicle Technologies Office, Water Power Technologies Office, and Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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