Efficiency Impacts of Distribution Secondaries

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***Abstract* — Distribution feeder models do not typically include secondary lines and distribution transformers. In general, sufficient data concerning the secondary impedances and individual customer demands has not been available to accurate assess the losses and voltage drops accrued across these portions of the feeder. However, feeder data collected through GIS and AMI programs may permit more accurate representation of system behavior at the customer level. In this paper, the impacts of typical secondary loss modeling assumptions and circuit configurations are evaluated against models derived from detailed secondary circuit data and field measurements collected by Consumers Energy.**

***Index Terms*—Efficiency, distribution system, distribution transformer**

I. Introduction

SERVICE transformers and secondary lines are not typically included in most distribution feeders models. Instead, the customer demand is represented in the model by the aggregate demand estimated at the primary side of the distribution transformer. In some cases, the modeled demand may even represent multiple transformers aggregated along a branch of the primary feeder. Without explicit representation, losses and voltage drop across the transformer and secondary circuits cannot be accurately gauged [1]. Even when the secondary circuit impedances are sufficiently accounted for, modeling assumptions concerning customer load allocation and diversity will also impact the accuracy of the estimations [2-4]. In this paper, the influence of typical secondary modeling assumptions on losses and customer voltage estimates are evaluated utilizing AMI and GIS data collected by Consumers Energy.

II. Secondary Circuits

Two of the secondary circuits evaluated as part of the overall study [5] are presented here to highlight the procedure and modeling sensitivities for two different secondary configurations. While analysis of these circuits provides insights into the sensitivities and modeling issues, they are not intended to represent every possible configurations or conditions which may arise.

Each secondary circuit model in the study was constructed utilizing specific GIS and circuit data. Additionally, individual customer demands – modeled at each hour across a full calendar year – were directly taken from AMI measurements of real and reactive power. Finally, an equivalent voltage source was derived utilizing additional AMI measurements taken at the secondary winding of the distribution transformer along with typical distribution transformer impedance data. The availability of voltage and power measurements at both the transformer secondary and at each customer allowed for model validation through comparison of the modeled and measured voltage drops and line losses.

A. Circuit A

Secondary study circuit A is composed of two overhead service drops of differing lengths and conductor sizes, as shown in Fig. 1 with the wire lengths indicated in feet. Additionally, AMI measurements locations are denoted in the figure and the corresponding measurements at each customer as well as the transformer secondary is provided in Fig. 2 and Fig. 3 respectively.

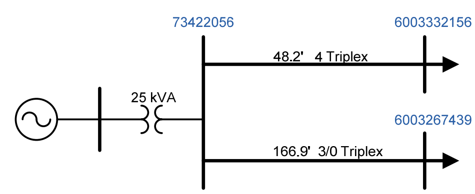

Fig. 1. Secondary Circuit A One-line Diagram

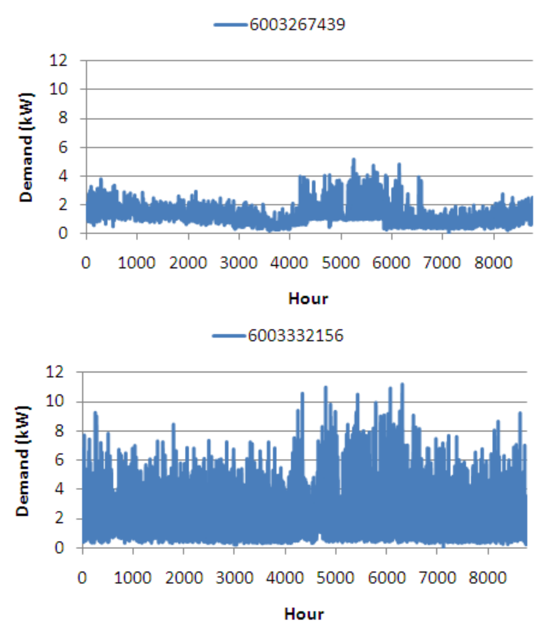

Fig. 2. Metered Customer Demands

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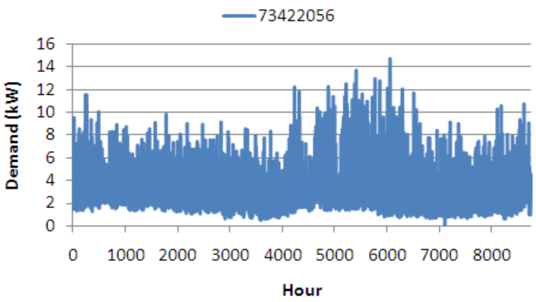

Fig. 3. Measured Demand at the Service Transformer Secondary of Circuit A

The measured and modeled voltage drop across each service is compared in Fig. 4 with each data point indicating the values on a one-hour interval. As shown, the measured voltage drop at 6003267439 (the longer, lightly loaded service) is on average slightly higher than modeled while an almost ideal one-to-one relationship exists between the measured and modeled values for the 600332156 bus. Additionally, errors from significant-digit rounding when calculating the voltage drop are clearly visible as incremental steps in the measured voltage drops.

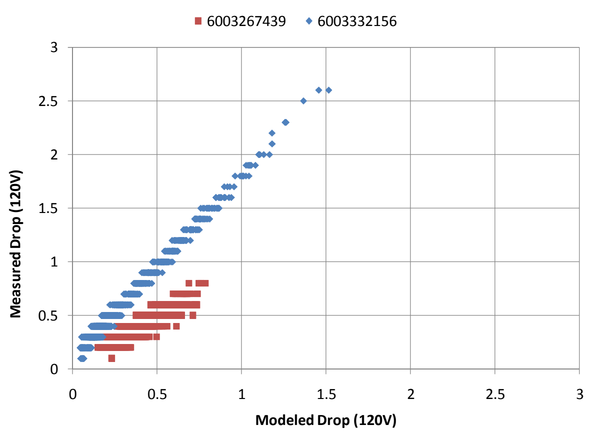

Fig. 4. Measured versus Model Secondary Voltage Drop of Circuit A

A comparison between modeled and measured line losses in the circuit is given in Fig. 5. In this case, the measured line losses tended to be almost twice that estimated in by the model. However, this difference may be due to difficulty in directly measuring losses as much as potential errors in the circuit model.

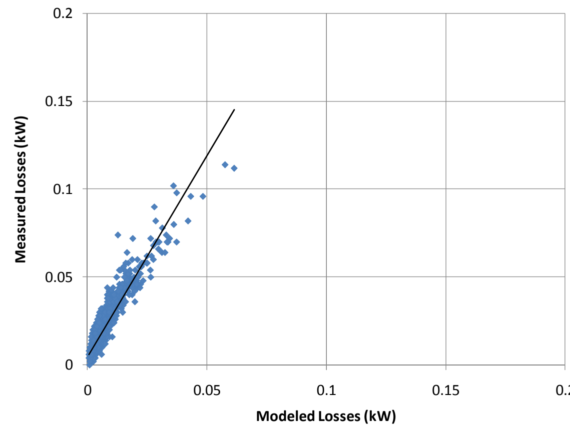

Fig. 5. Measured versus Model Line Losses for Circuit A

B. *Circuit B*

This secondary circuit is characterized by a long common secondary supplying multiple service drops at varying distances along the secondary, as shown in Fig. 6. Additionally, service drops lengths range from 50 to over 200 feet. Comparison of the model and measured voltage drops and losses from the transformer secondary to each customer meter, Fig. 7 and Fig. 8 respectively, indicates a relatively good fit between model and measurement data. This circuit is also characterized by a significant amount of voltage drop between the transformer and the customer meter as a result of the length of the secondary lines and conductor sizes.

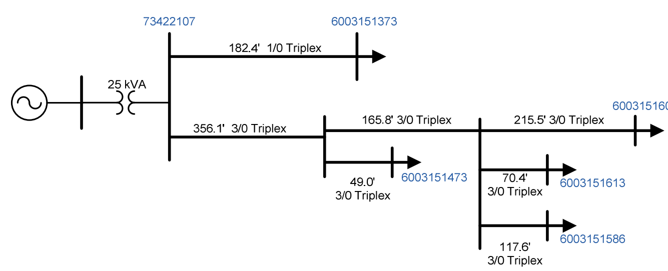

Fig. 6. Secondary Circuit B One-line Diagram

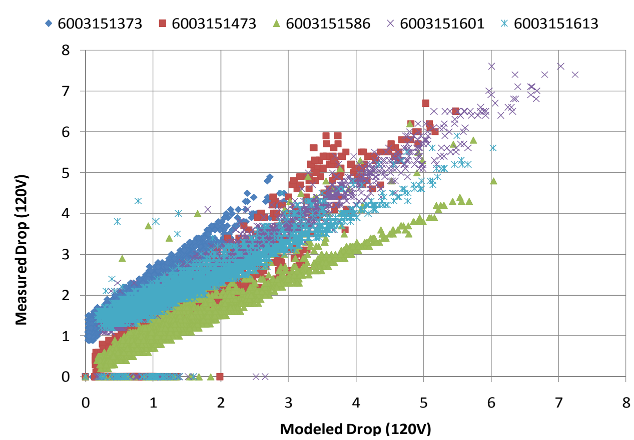

Fig. 7. Measured versus Model Secondary Voltage Drop for Circuit B

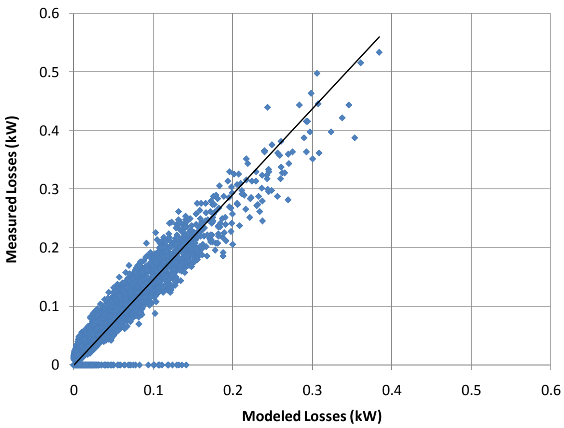

Fig. 8. Measured versus Model Line Losses for Circuit B

III. Secondary Modeling Analysis

The loss estimation and voltage drop sensitivities were evaluated for each study secondary using four different modeling approaches. These modeling approaches consider differing levels of detail and modeling simplification. Results should indicate the degree to which simplifying assumptions affect estimation of secondary losses. The four modeling approaches are defined as the following:

Full AMI: Hourly demand for each load is defined by the AMI measurements for both kW and kvar while the circuit configuration is taken directly from the utility circuit model. This case is considered the ideal model case and is used as the benchmark to which the other cases are compared.

Fixed pf: Hourly demand for each load is defined by the AMI measurement for kW with a constant power factor of 0.95 lagging. The circuit configuration is taken directly from the utility circuit model. This case examines the ramification of not fully capturing the variability of individual customer reactive power demands.

Aggregate Profile: The circuit configuration is taken directly from the utility circuit model. However, hourly demand variations are based on single normalized load shape derived from the substation demand measurements and peak demand are allocated based on measured customer annual kWh. This case represents the effect of not fully representing the load diversity at the individual customer level. The implications of this assumption are illustrated in Fig. 9 by larger variations seen in the AMI measurements compared to the equivalent aggregate load profile.

Generic Service: Loads are the same as for the full AMI case; however, the circuit model is simplified by assuming a direct service drop (100 feet of 1/0 triplex wire) for each customer meter. This case is provides an indication of how much impact not having an accurate representation of the secondary configuration and conductor sizes may have to the estimated losses.

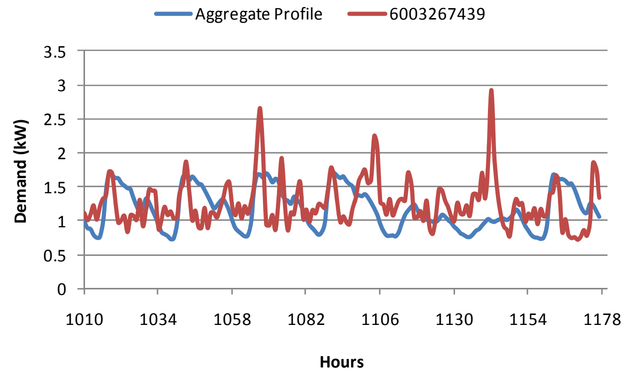

Fig. 9. Customer Hourly Demand from AMI and Aggregate Model

It is important to note, that the changes in the customer voltages during these defined sensitivity cases will not impact the modeled customer demand as each load was explicitly defined to match the AMI measurement at each hour. Consequently, the subsequent loss sensitivity evaluations cannot directly account for the influence CVR may have on the loss estimations. However, examination of the minimum as well as the average model voltages will provide qualitative insights into the each underlying assumption's influence of estimating secondary losses.

Modeling simplifications with respect to the estimation of customer voltage is first evaluated through simulation of the different modeling approaches on the four study circuits. The simulated voltage results are presented in Fig. 10 and Fig. 11. The fixed power assumption does not have a significant impact to the voltage estimation at this level of load aggregation. However, this assumption may have more of an impact when applied to an entire feeder model.

As expected, the aggregate profile overestimates the customer voltages during peak loading times but provides similar average voltage results. Furthermore, the transformer secondary voltage is also over estimated during the peak by as much as three volts. These results indicate potential difficulties accurately assessing customer-level circuit behavior utilizing substation level data.

Use of a generic equivalent service impedance resulted in inaccurate estimation of the peak voltage by as much as 4 volts and as much as 1 or 2 volts on average. In this case, the assumed secondary impedances resulted in higher estimates overall. Naturally, the modeled results were closer for the circuits whose configuration was similar the assumed direct service drop configuration.

In general, the slightly higher customer voltages which resulted from not sufficiently modeling the load diversity and the secondary circuits may under predict the reduction in demand and therefore secondary loss reduction due to CVR. Still, more research may be needed to identify relationships between individual customer demand and CVR values for future modeling efforts.

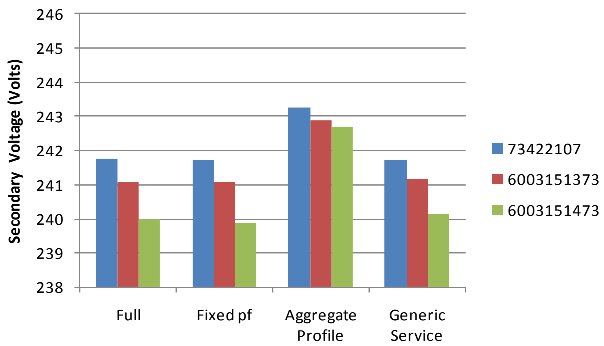

Fig. 10. Minimum Non-coincident Bus Voltages (Circuit A)

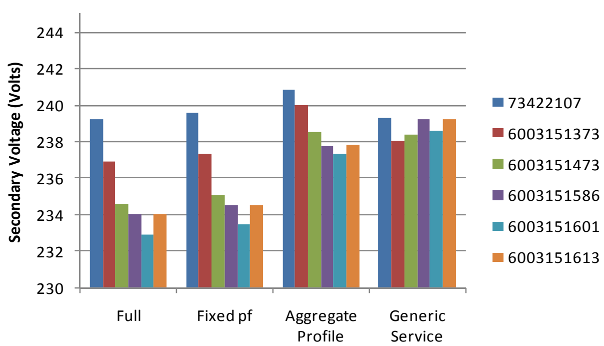

Fig. 11. Minimum Non-coincident Bus Voltages (Circuit B)

Summary consumption/demand and percent loss results for previously outlined sensitivity cases as applied to the test circuits are provided in Table 1 and Table 2. Some summary findings from the loss results was the annual no-load losses were the least affected in the assumptions cases as the individual circuit and load changes were insufficient to influence the average primary voltage in the circuit models. The fixed power factor assumption has a minimal effect on loss estimates. This impact may have a more significant impact when voltage reduction (CVR) is fully considered.

The largest deviations in the annual secondary loss estimations occurred on circuits with extensive secondary lines serving multiple customers. Secondary peak losses can be significantly underestimated when using a highly coincident load profile due to lower I^2R loss estimates. The impact of the generic service assumption in the loss estimates will depend on how representative the equivalent model is of the typical feeder secondaries. Unsurprisingly, the largest secondary loss estimate differences below correlate with the most significant differences in voltage estimates.

TABLE 1
SECONDARY CIRCUIT ANNUAL CONSUMPTION AND LOSSES

	Model Case	Total Consumption (kWh)	Losses (kWh)			
			Total	Line	Xfmr Load	Xfmr No-Load
Circuit A	Full AMI	25645	549.7	43.1	50.8	455.8
	Fixed pf	25648	552.7	44.6	52.4	455.7
	Aggregate Profile	26003	527.4	30.2	41.5	455.7
	Generic Service	25641	545.6	37.5	52.3	455.7
Circuit B	Full AMI	41972	899.6	315.8	137.4	446.4
	Fixed pf	41931	858.5	287.6	123.9	447
	Aggregate Profile	41854	778	221.7	109.8	446.5
	Generic Service	41718	645.6	63.6	135.6	446.4

TABLE 2
TEST CIRCUIT PEAK DEMANDS AND LOSSES

	Model Case	Total Consumption (kWh)	Losses (kWh)			
			Total	Line	Xfmr Load	Xfmr No-Load
Circuit A	Full AMI	14.71	0.25	0.09	0.11	0.05
	Fixed pf	14.72	0.26	0.1	0.11	0.05
	Aggregate Profile	5.61	0.08	0.01	0.02	0.05
	Generic Service	14.7	0.24	0.08	0.11	0.05
Circuit B	Full AMI	20.86	0.6	0.35	0.21	0.05
	Fixed pf	20.85	0.59	0.33	0.2	0.05
	Aggregate Profile	9.1	0.18	0.09	0.04	0.05
	Generic Service	20.6	0.34	0.08	0.2	0.05

IV. SECONDARY DATA ANALYSIS

Data from AMI metering on customers and some transformers enabled us to better evaluate losses and voltage drops on transformers and secondaries.

A. *Secondary Line Losses*

Figure 12 shows a cumulative distribution of secondary line losses for 26 secondaries on the circuit. The monitoring period was one year. Each of these secondaries had AMI at all customers on the transformer as well as a meter on the secondary side of the transformer. Losses were estimated from the difference between the kilowatt-hour readings at the transformer meter and the sum of all of the customer meters. Results were checked to try to exclude secondaries with obvious unmetered load. Unmetered loads were identified by finding correlation coefficients between the transformer measurement and the sum of the customer meter measurements. Those with an R^2 below 0.999 were excluded. Some of those excluded had obvious lighting load signatures (unmetered). The overall average secondary line losses were 0.87% for this set of customers; the median losses were 0.63%.

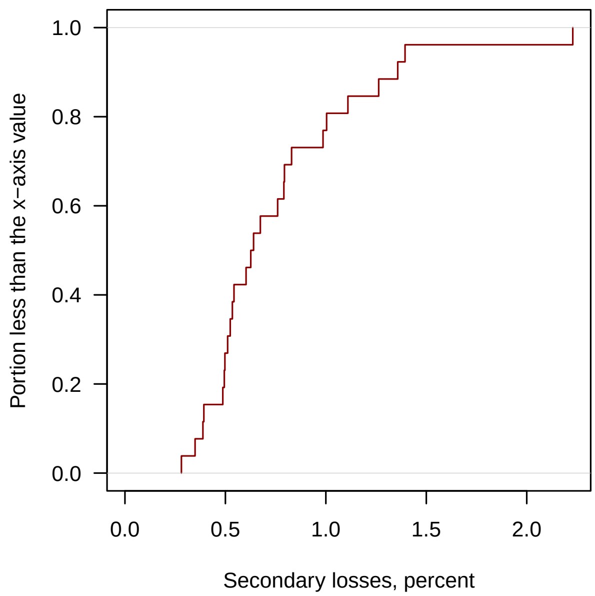

Fig. 12. Secondary line loss probability distributions.

B. Transformer Load Losses

Having AMI metering on several transformer secondaries provides an opportunity to estimate transformer load losses. The transformer load losses were derived from the monitored load current squared times the transformer resistance (I^2R). Fig. 13 shows cumulative probability distributions for transformer load losses on 86 transformers on this circuit.

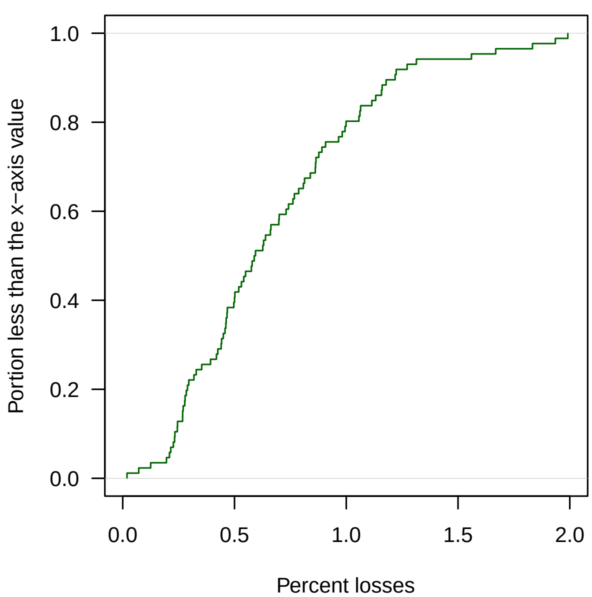

Fig. 13. Transformer load loss distributions.

Transformer loading correlated well with line losses, as shown in Fig. 14. Overall, on this subset of monitored transformers, transformer load losses averaged 0.76%.

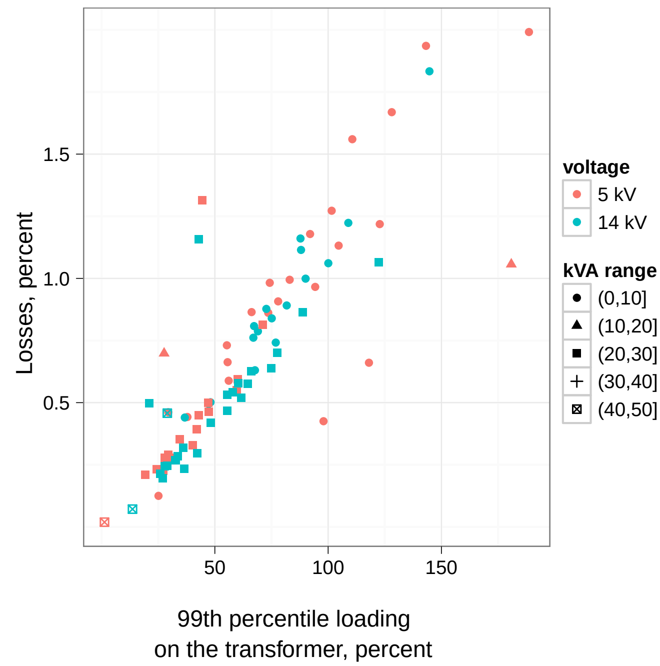

Fig. 14. Transformer load losses versus different factors.

C. Secondary Voltages

The customer voltages generally ranged between 118 and 126 V on this circuit. Fig. 15 shows a cumulative probability distribution for the voltages on this circuit. The median customer voltage for this circuit was near 122 V. These customer voltages show that there is significant room to lower voltages on these two circuits and still be above the ANSI C84.1 lower range of 114 V. Figure 16 shows a cumulative probability of voltages at peak load. There is less room to reduce voltage at peak load, mainly because of secondary voltage drop.

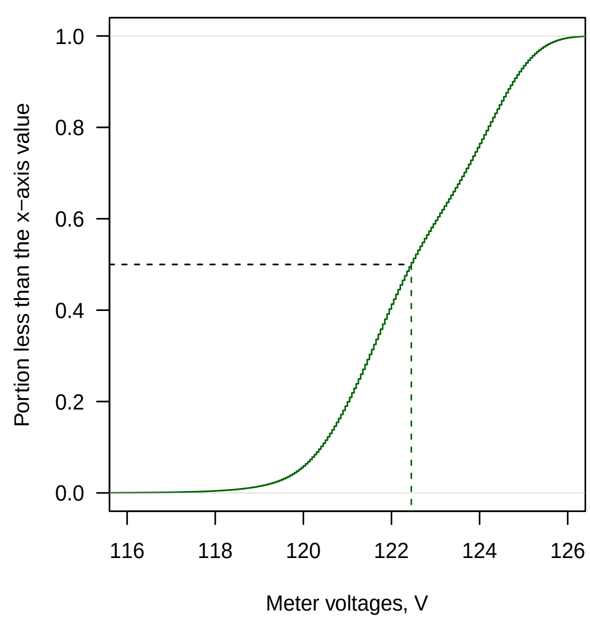

Fig. 15. Meter voltage probability distributions.

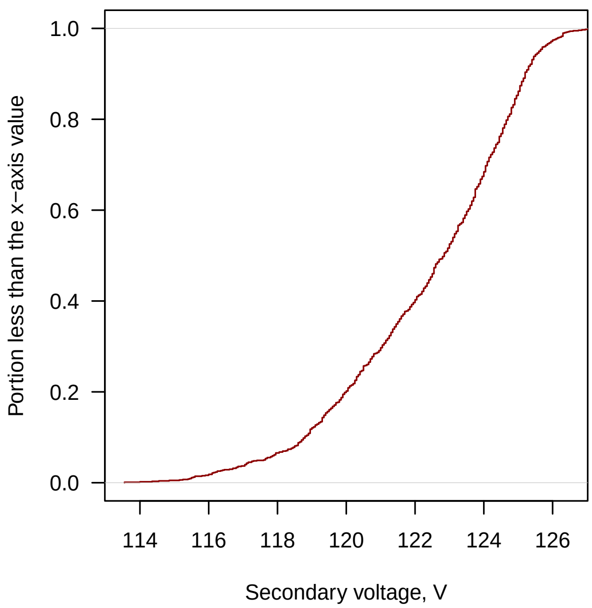

Fig. 16. Meter voltage probability distribution at peak load.

D. Secondary Voltage Drops

With measurements at several transformers and the customer meters fed from those transformers, voltage drops across the secondary system can be found. Figure 17 shows a cumulative distribution of voltage drops measured at the circuit's summer peak load. Voltage drops at peak were generally between 0.5 and 2 V. Note that voltage drops were negative for approximately 10% of measurements, indicating non-negligible measurement error. For these cases, the customer meter voltages were higher than the transformer voltages.

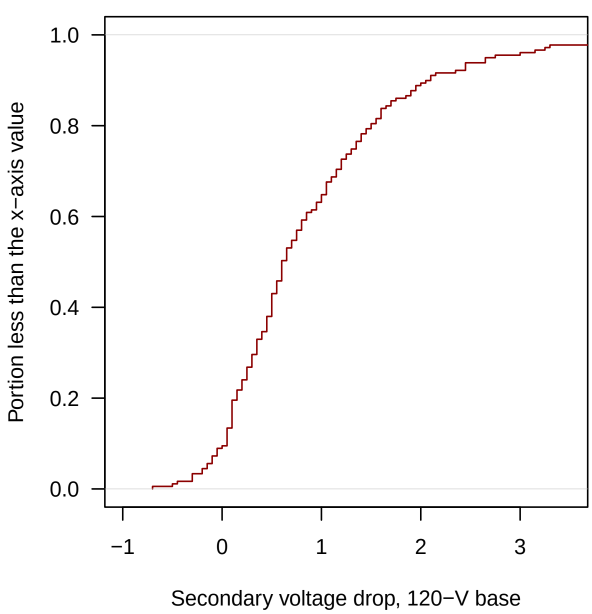

Fig. 17. Peak-load secondary voltage drop probability distributions.

V. Conclusions

As newer end-user connected technologies continue to shift the focus of distribution system modeling towards the customer level, model refinement will be increasingly needed as this level. As shown, secondary modeling assumptions intended to either simplify the circuit or to account for a lack of detailed information can significantly misrepresent customer voltages. In particular, not accounting for diversity in the customer load variations can significantly underestimate the voltage drops along the secondary circuits. While secondary losses are also general underestimated, they are still expected to be a relatively low percentage of the total system losses.

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Biographies

Jason Taylor (M'98) received his B.S. and M.S. degrees in electrical engineering from Mississippi State University and his Ph.D. from Auburn University where his research concentrated on power system parameter identification methods. He is currently a Senior Project Engineer in the systems analysis and studies group at EPRI, Knoxville, where his current research includes power system efficiency, PEV distribution system impacts, energy storage modeling, and developing metrics and analysis for evaluation of Smart Grid and distributed resource on the electrical power system. Before coming to EPRI, Jason worked as a Power Systems engineer at Electrotek Concepts performing transmission interconnection studies and wind turbine modeling.

Tom Short (M'90–SM'98) is with EPRI at an office in Burnt Hills, NY. Before joining EPRI in 2000, he worked for Power Technologies, Inc. for ten years. Mr. Short has a Master's of Science degree in Electrical Engineering from Montana State University (1990). Mr. Short authored the *Electric Power Distribution Handbook* (CRC Press, 2004). In addition, he led the development of IEEE Std. 1410-1997, *Improving the Lightning Performance of Electric Power Overhead Distribution Lines* as the working group chair.