Summary of Modeling Results for Distribution Efficiency Case Studies

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***Abstract*--The EPRI Green Circuits project was a collaborative effort of 22 utilities. The main goal of the project was to evaluate ways to improve distribution efficiency. For this evaluation of efficiency improvements, 66 circuit case studies were used. Each circuit was modeled in detail from the substation to each customer meter and analyzed using the long-term dynamic distribution system electrical simulation package. Nearly all of the circuit models were augmented with historical circuit-measurement data that allowed for hourly-resolution simulation of the operation of the circuit for actual load patterns for each hour in a calendar year (8760 hours). All sources of losses through both daily and seasonal load changes were found with these circuit models. This paper provides a summary of the collective results from 66 circuits modeled.**

***Index Terms*-- power distribution; distribution system losses; energy efficiency; power delivery efficiency.**

I. INTRODUCTION

This paper provides a summary of the collective results from 66 circuits modeled as part of the EPRI's Green Circuit project. The main goals of the modeling were to:

- Quantify average and peak losses.
- Determine secondary and transformer losses.
- Quantify voltage profiles along the primary, through the transformer, and to customers.
- Evaluate options to reduce losses, including phase balancing, reactive power improvements, re-conductoring, transformer replacements, and circuit reconfigurations.
- Evaluate voltage-reduction options to reduce peak and/or average consumption.
- Evaluate methods to flatten voltage profiles to enable better voltage reduction.

The 66 circuits studied encompassed many different types of distribution circuits that varied in design practices, load types, voltage class, voltage-regulation techniques, and var control practices. In addition, the circuits covered many different geographical locations and urban and rural environments of varying degrees. The circuit modeling implementation also varied from circuit to circuit, depending on circuit measurement data provided or not provided.

Circuit variability may have reduced the overall consistency across the circuits studied. EPRI also attempted to address each circuit uniquely with utilities' specific interests in mind. With this said, even when a "standardized" approach was taken across all circuits, the uniqueness of each circuit still presented results that were not all inclusive but required further investigation of individual circuits to explain those differences. These further investigations provided additional insight and understanding and some general conclusions can still be made. The circuits were not selected randomly, and EPRI does not claim that the circuits are "representative." The circuits were self-selected by utility participants. Each utility chose circuits based on their goals. Some utilities chose circuits from different operating regions. Some utilities chose circuits based on availability of monitoring data or availability of modeling data. Some utilities chose circuits based on voltage or urban verses rural.

II. GENERAL CHARACTERISTICS

This section is intended to provide the reader with a concise summary of the various circuits analyzed.

Please note that each circuit is coded with a two-letter designation that is consistent throughout the graphs. Each of the circuits was self-selected by the utility. No statistical weighting or normalization has been done for these circuits. Table I provides the circuits' maximum, minimum, and average values for the parameters listed:

- Load Factor
- Load Density – the number of customers per total length of primary line (#customers / primary mile)
- Peak Load to Connected kVA– the percentage of peak load to the transformer connected kVA
- Residential load – the amount of residential load customers out of total number of customers
- Unbalance Load – the amount of unbalance current at the head of the feeder.

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TABLE I
SUMMARY OF CIRCUIT CHARACTERISTICS

Parameter	Max	Min	Average
Load Factor	71%	29.3%	46%
Load Density (#customers / primary mile)	370.7	1.1	75.5
Peak Load to Connected kVA	101%	18%	42%
Residential load	100%	22.60%	78%
Unbalance Load	75%	<1%	10%

Average power factors on circuits varied significantly, as shown in Fig 1 and 2. Sixty-one percent of circuits had a power factor above 0.98, while 12% of circuits had less than a 0.9 power factor.

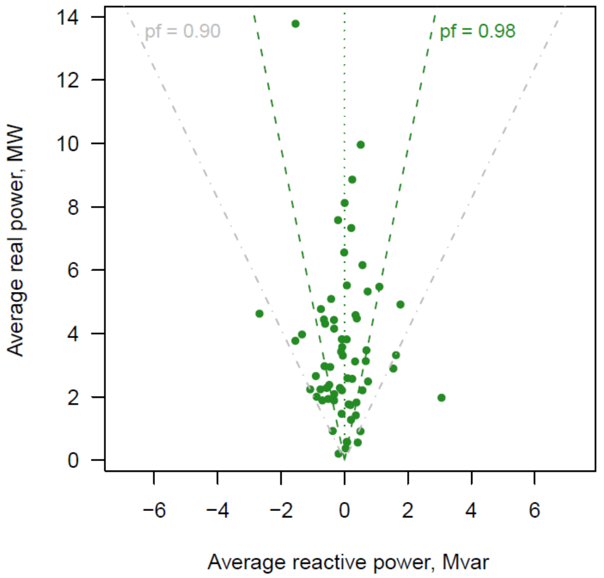

Fig. 1. Average power factors by circuit.

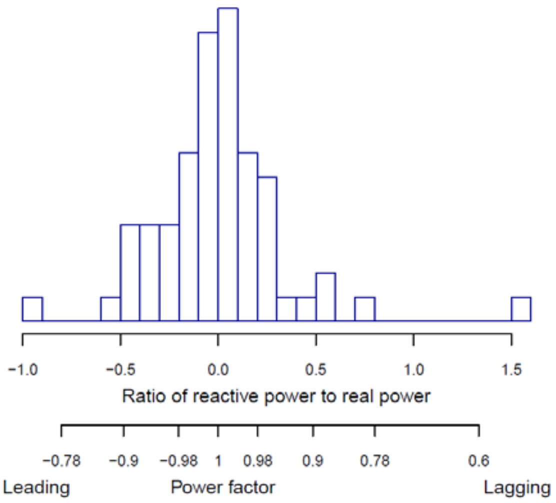

Fig. 2. Average power factors by circuit.

Fig. 3 provides a breakdown, by voltage class, of the circuit lengths. Circuit length in this graph is defined as the distance to the farthest load from the substation. The 5-kV, 15-kV, 25-kV, and 35-kV class circuits had an average length of 2, 6.7, 16.1, and 9.4 miles, respectively. The longest feeder was a 69-mile, 25-kV feeder, which was lightly loaded (450 kW at peak). The shortest feeder was a 15-kV class feeder that was 1.3 miles long. This was a circuit dedicated primarily to commercial loads.

Fig. 4 shows a breakdown, by voltage class, of the number of customers on each of the circuits studied. The 5-kV, 15-kV, 25-kV, and 35-kV circuits had average numbers of customers of 372, 1355, 1981, and 2951, respectively. The largest number of customers on a single feeder was 3885 on a 35-kV feeder. The smallest number of customers was 58 on a 15-kV class circuit that was dedicated primarily to commercial loads.

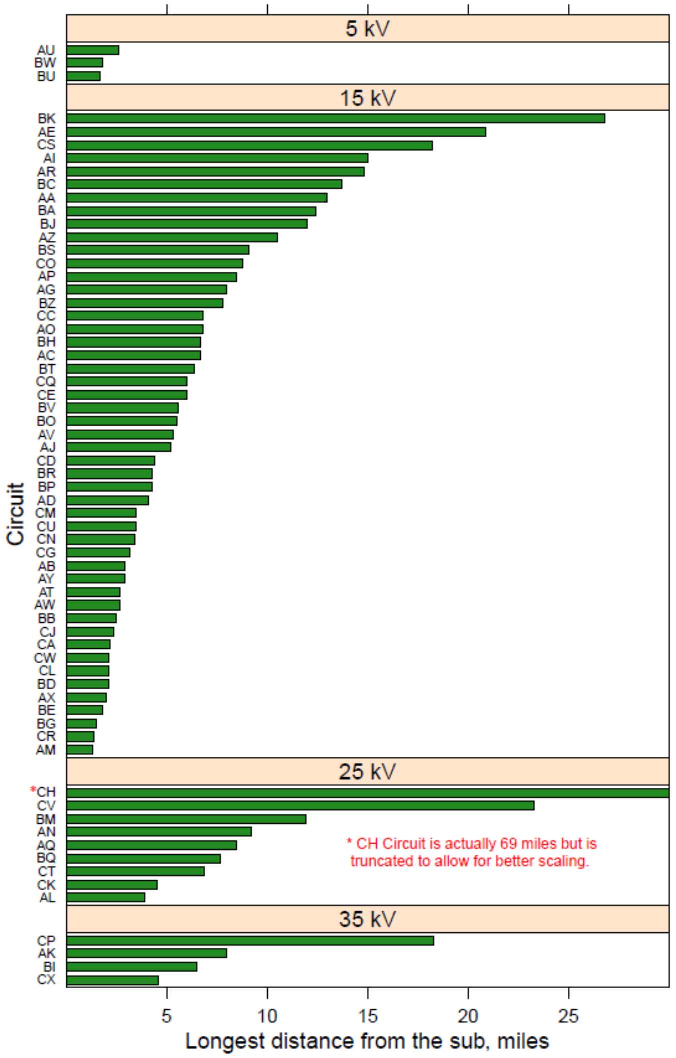

Fig. 3. Circuits by voltage and distance from their substation.

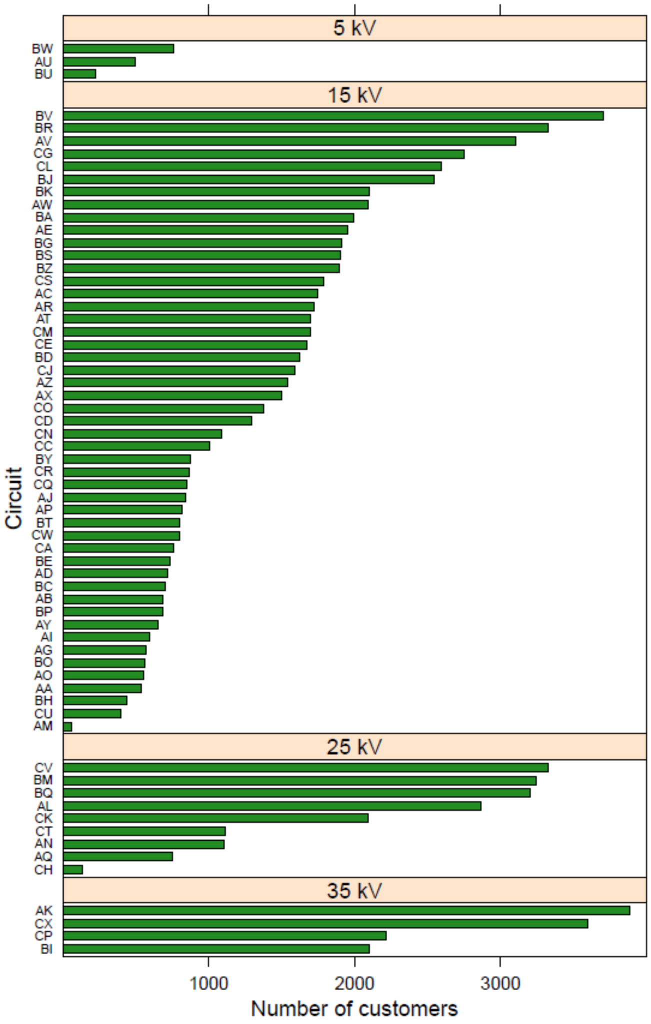

Fig. 4. Number of customers per circuit.

III. GENERAL LOSS CHARACTERISTICS

This section is intended to provide the reader with an overall view of the circuits' loss results. See Table II and Table III for summaries of percent losses from simulation results. Table III is based on the same data as Table II, but losses were weighted by circuit results. Because more heavily loaded circuits (generally higher load densities) had lower relative losses, the weighted results show slightly smaller percentage losses.

The average and peak losses are displayed in Fig. 5 through Fig. 7. The losses shown in these figures are broken down into primary, secondary, and service transformer's load and no-load losses. Generally, the longer rural feeders tended to have higher losses compared to the shorter urban feeders. Additional points of interest are as listed:

Total losses – Total distribution losses, not including the substation transformer averaged 3.64% of total consumption. Seventy-five percent of circuits had losses exceeding 2.49%, and 25% of circuits had losses exceeding 4.35%. The largest category of losses was no-load losses, which averaged 42% of the total average losses.

Line losses – Line losses averaged just under 1.34% of total consumption. Circuit length is a reasonably good predictor of percentage line losses. Line losses had the most spread among circuits.

Transformer no-load losses – Transformer no-load losses averaged about 1.4% of total consumption. These losses were the most consistent across circuits, depending mainly on transformer age and transformer utilization (connected kVA versus load).

Secondary losses – Secondary losses averaged about 0.3% of total consumption. For the most part, these tended to be low.

Demand – At peak load, losses average 4.8% of consumption. Of all circuits, 75% had peak losses exceeding 2.99%, and 25% of circuits had losses exceeding 5.87%. One circuit had peak losses of 16.5%. At peak, 72% of losses were line losses.

TABLE II
DISTRIBUTION CIRCUIT LOSS STATISTICS, PERCENT

		Quartiles		
	Average	**25%**	**50%**	**75%**
Primary line losses	1.40	0.61	1.04	1.84
Transformer load losses	0.38	0.24	0.34	0.46
Transformer no-load losses	1.59	1.03	1.49	1.89
Secondary line losses	0.31	0.16	0.27	0.44
Total losses	3.64	2.52	3.09	4.32

TABLE III
DISTRIBUTION CIRCUIT LOSS STATISTICS WEIGHTED BY LOAD, PERCENT

		Quartiles		
	Average	**25%**	**50%**	**75%**
Primary line losses	1.34	0.64	1.03	1.83
Transformer load losses	0.35	0.23	0.35	0.41
Transformer no-load losses	1.39	0.89	1.34	1.82
Secondary line losses	0.31	0.18	0.27	0.44
Total losses	3.35	2.21	2.96	3.91

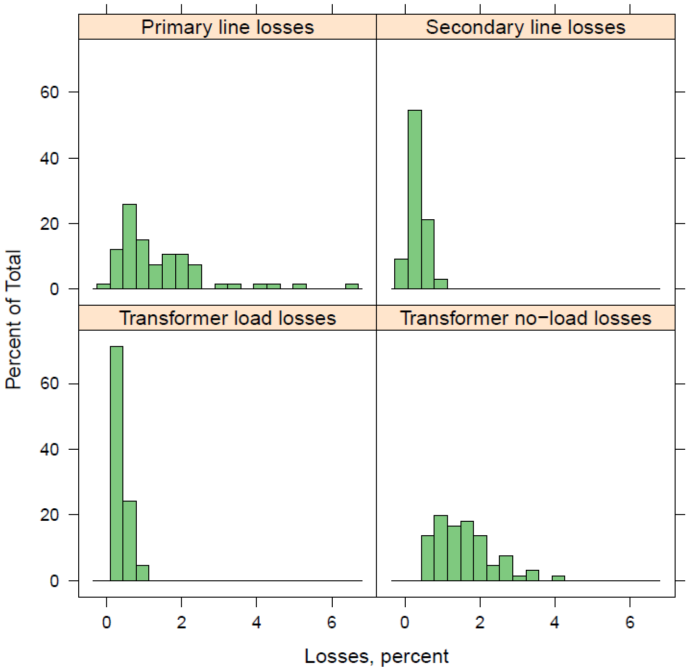

Fig. 5. Percent losses by location

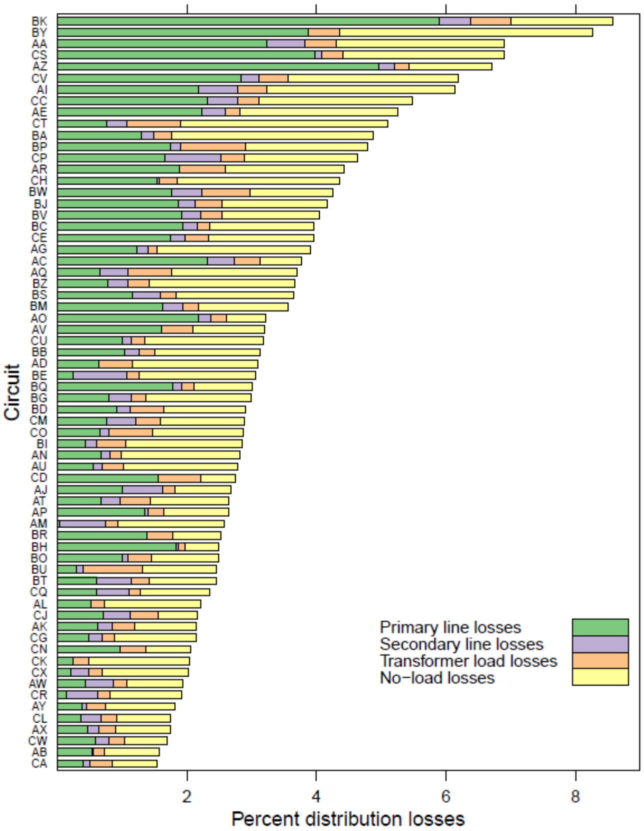

Fig. 6. Circuit loss breakdowns in average percentage

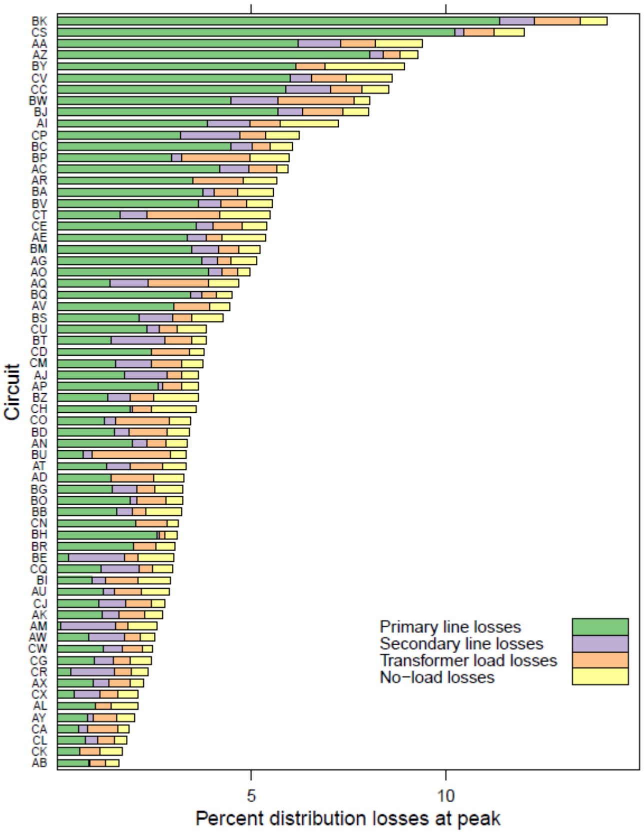

Fig. 7. Circuit loss breakdowns in peak percentage.

IV. GENERAL LOSS CHARACTERISTICS

This section summarizes several improvement options that were investigated. For every circuit, the following lower-cost improvement options were evaluated: reactive-power optimization, phase balancing, and voltage optimization. Other options such as re-conductoring, transformer replacements, and circuit reconfigurations were modeled based on the circuit characteristics and requests of the utility.

A. *Idealized var improvement*

The impact of load reactive power and feeder var improvement options was analyzed by evaluating an idealized var improvement, with results given in Fig. 8. With this approach, the reactive power component of all loads is set to zero, and capacitors are turned off, resulting in approximately unity power factor. For those circuits where the idealized var case shows that significant improvements are possible, more realistic capacitor application and control were investigated.

On average, the ideal var improvements reduced the average line losses by 6.8 kW, or 17%. The circuit with the most room for improvement (Circuit AZ) had too many fixed capacitors. In this particular case, the circuit power factor was good at peak but operated at an excessively leading power factor for most of the rest of the year. This increases the average current flow on the lines.

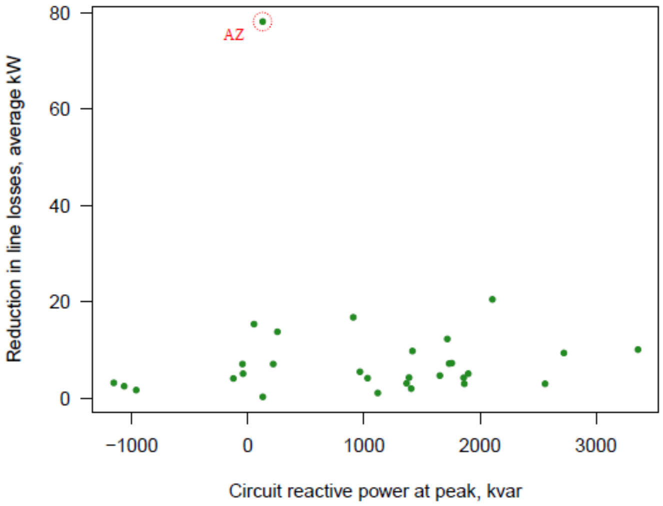

Fig. 8. Reduction in line losses with ideal var improvement.

B. *Phase-balancing*

An idealized phase-balancing case was also conducted for each circuit model. Unbalance increases line losses because the more heavily loaded phase conductors will have much higher losses because the line losses are a function of the current squared. There will also tend to be higher residual currents in the neutral, leading to more losses. The idealized phase balancing is done by re-adjusting the load to allocate it equally across phases. This forces the phases to be balanced at the substation. This assumes that much of the line losses are in conductors close to the substation. Fig. 9 shows the reduction in line losses versus the amount of residual current.

If phase balancing appeared to be an option, more realistic balancing options were attempted by moving single-phase taps. As can be seen in Fig. 9, some circuits actually got worse, mainly because the balancing only balances at the substation, and this can create further unbalance downstream. The "CP" circuit had the greatest line savings in average energy. In this circuit, the average and peak unbalance was reduced to 1.5% from a base-case unbalance of 16.5%. The "BS" circuit had an increase in average line losses due to the fact that balancing the circuit at peak created higher unbalances during the off peak hours.

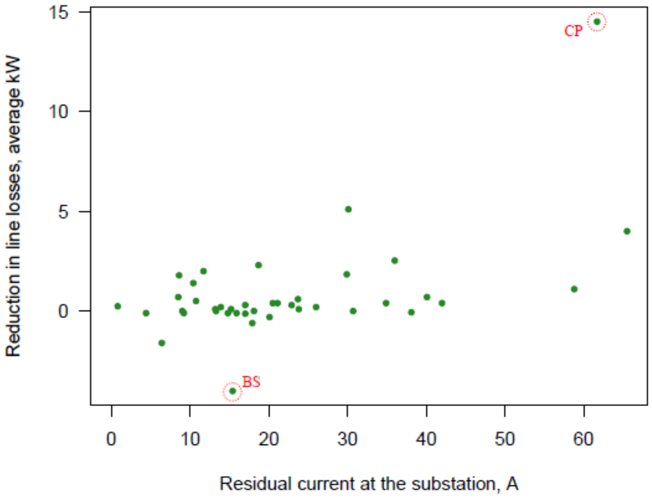

Fig. 9. Reduction in line losses with ideal phase balancing.

C. *Re-conductoring*

Re-conductoring was also considered for several circuits, as shown in Fig. 10. Re-conductoring was done on a case-by-case basis. Conductor replacement was determined by utility requests or decided by EPRI on the basis of targeting conductors with relative high I^2R losses. The conductor upgrade sizes were determined by the present utility inventory or upgrade plans or arbitrarily selected for analysis reasons. Because of this variability in re-conductoring studies, it is difficult to say much about the results, because each case was different regarding the amount of re-conductoring done and the conductor sizes involved. With this said, circuits that tended to be higher in line losses—rural feeders with long conductors— tended to show more improvement from re-conductoring than urban feeders.

D. *Voltage optimization*

Voltage optimization is another approach applied to all circuits. Voltage is reduced (while still keeping within limits) to improve end-use efficiency and reduce energy supplied. Most of the gain is from reduced end-use consumption. The standardized voltage reduction case involves the following assumptions:

- Use end-of-line feedback on all LTCs and voltage regulator controllers.
- Voltage set point = 118.5 V (this value varied on each circuit due to voltage drop beyond this monitored point).
- Bandwidth = 2 V (+/– 1 V).
- CVR factor for watts = 0.8.
- CVR factor for vars = 3.0.

Although voltage feedback from monitored points at the end of a regulated line section is possible, it is not always easy to implement. More commonly, line-drop compensation would be used to control regulators. It is expected that line-drop compensation could achieve results close to those reported with voltage feedback, and this has been verified in some cases where the line-drop compensation was modeled.

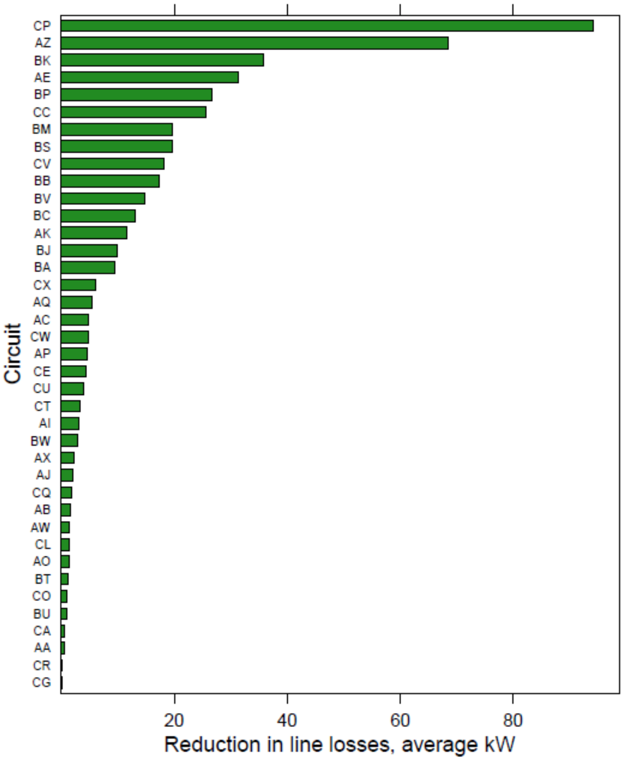

Fig. 10. Re-Conductoring impact on line losses.

Fig. 11 shows the reduction in load computed when this standardized voltage-optimization scheme was used. The median reduction in energy was 2.34%, with upper and lower quartiles of 1.69 and 3.13%. While CVR factors are expected to vary from circuit to circuit, a constant CVR factor was used in this analysis. Because a constant CVR factor was used, these simulations mainly show how much room there is to drop voltage across the circuit throughout the course of an annual cycle. Most of the circuits had significant room to reduce voltage; most regulator controls had relatively high set points, and use of line-drop compensation was unusual for the circuits in this study. On a circuit such as "CU" in Fig. 11 (the circuit with the least room for voltage improvement), the voltage profile was already fairly optimized with the use of substation and mid-line regulators both utilizing load-drop compensation; therefore, a smaller reduction was realized.

As noted in Table IV, reduced end-use consumption made up 95.6% of overall energy savings from voltage optimization.

Reductions in no-load losses composed 4.1% of total savings, with minor savings from load losses.

TABLE IV
AVERAGE ENERGY SAVINGS FROM VOLTAGE OPTIMIZATION BY COMPONENT

	Breakdown of Overall Energy	*Voltage Optimization Energy Savings*	
		Savings per Component	Portion of Total Savings by Category
No-Load Loss	1.6%	5.6%	4.1%
Load Loss	1.8%	0.6%	0.2%
Consumption	96.6%	2.3%	95.6%

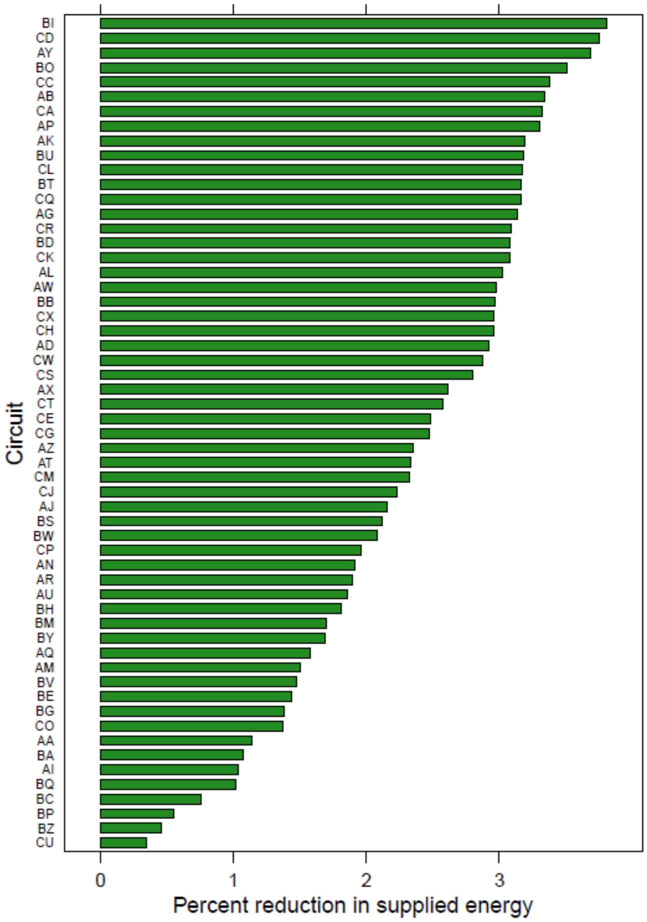

Fig. 11. Reduction in energy supplied with voltage optimization.

Fig. 12 shows a plot of the percent energy savings versus the average primary voltage. In this figure, 53% of the circuits are represented in the upper right quadrant of the graph, indicating a trend that the higher the average primary voltage, the higher the energy savings with voltage optimization implemented. However, there are some circuits showing less energy reduction than some of the circuits that had lower average voltages. This illustrates the fact that there are many variables in addition to average voltage that determine the amount of energy savings that are achievable with voltage optimization. One critical variable is where the load is concentrated on the circuit. The figure is for the average primary voltage, but the more important voltage is the customer voltage, which is not necessarily the same as the primary voltage.

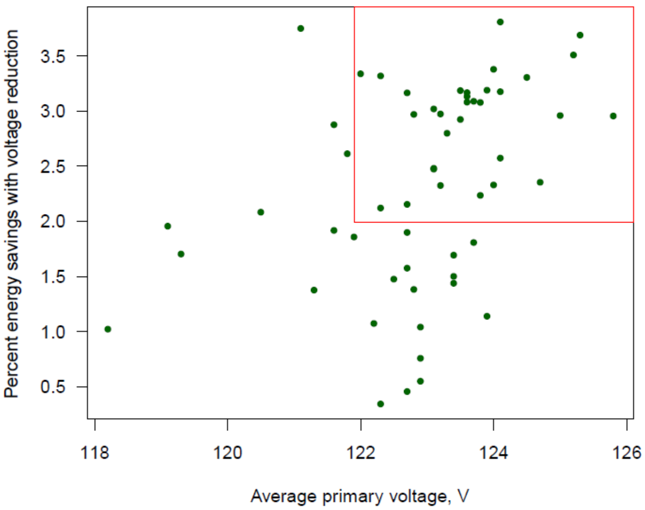

Fig. 12. Average primary voltage prior to reduction versus reduction in energy.

V. CONCLUSIONS

The set of circuits analyzed was very diverse. Circuits varied based on design approach, voltage class, circuit lengths, load density, and so on. Although the circuits varied a great deal, certain general characteristics could still be identified. The circuits that did not follow these general characteristics provided additional insight.

The optimal efficiency improvement approach depended on the circuit. On average, the reconductoring and ideal var control resulted in the greatest reduction in losses.

Voltage optimization applied full-time provided the most energy reduction by improving end-use efficiency as well as reducing no-load losses. This option provided benefit on almost all circuits. The circuits that showed the most improvements with voltage optimization had sufficient voltage margin already existing in the feeder. Additional improvement is possible by flattening voltage profiles by phase balancing, circuit reconfigurations, or with additional voltage regulators or capacitors.

VI. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES

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His employment experience included Raytheon in Sudbury, MA where he worked in the Power and Electronic Systems Department. At Raytheon he was awarded the 2006 Raytheon Technical Honors Award for Peer and Leadership Recognition for Outstanding Individual Technical Contribution and also received a 2005 Raytheon Author's Award for work on Phase-Shifted Transformers for Harmonic Reduction.

Mr. Arritt has spent most of his career designing and modeling power systems from the electronics level to ac generation. Recently, Mr. Arritt has been actively involved in distributed generation impact studies, the EPRI Green Circuits effort, and various other power distribution related work.

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Mr. Short led the development of IEEE Std. 1410-1997, as Chair of the IEEE Working Group on the Lightning Performance of Distribution Lines. For this effort, he was awarded the 2002 Technical Committee Distinguished Service Award.

Daniel Brooks (M'92, SM 2007) received his B.S. and M.S. degrees in electrical engineering from Mississippi State University and his M.B.A. degree from University of Tennessee-Martin. He manages the EPRI Power Delivery and Utilization sector's Grid Operations and Planning research programs. In this position, he manages and conducts power systems engineering analytical studies spanning transmission, distribution, generation, and system operations. Before joining EPRI, he worked for over nine years with Electrotek Concepts managing and conducting similar studies. Mr. Brooks is a registered professional engineer in the state of Tennessee and is a senior member of the IEEE Power Engineering Society.