Voltage Reduction Results on a 24-kV Circuit

R. C. Belvin, *Member, IEEE*, and T. A. Short, *Senior Member, IEEE*

***Abstract*—This paper describes findings from a field trial of voltage reduction on a 24-kV circuit in North Carolina. The depth of voltage reduction was limited by commercial customers with off-nominal transformer taps and by customers with transformer and secondary issues. Voltage measurements from advanced metering provide insight on the importance of distribution transformers and secondaries when reducing voltage.**

***Index Terms*—Power distribution, efficiency, conservation voltage reduction.**

I. Introduction

VOLTAGE reduction or conservation-voltage reduction (CVR) provides opportunities to reduce energy consumption by improving end-use efficiency. In this paper, we describe field measurements on two circuits participating in a research project to evaluate the performance of voltage reduction [1]. The ANSI C84 [2] range A is from 114 to 126 V for service voltages. The objective was to operate service voltages in the lower part of range A.

As part of the research project, the circuit was operated in two voltage control modes on alternating days. Voltage was controlled from SCADA by changing the settings group on a voltage regulator controller for the substation LTC. The control mode changed at midnight. During normal mode, the LTC control had a setpoint of 124.5V +/- 1.5V on a 120-V base with no line-drop compensation. During reduced-voltage mode, the LTC control had a lower setpoint plus line-drop compensation to lower voltage more under lighter load.

In the field trial circuits, an LTC-controlled transformer supplied two feeders with a peak load of approximately 27 MW serving almost 5000 customers (see Fig. 1). The nominal primary voltage was 23.9Y/13.8 kV. The most distant point on the circuit was 4.5 miles (7.2 km) from the substation, and the peak primary-side voltage drop was estimated to be 3 V on a 120-V base.

This circuit should have been an ideal candidate for voltage reduction: the circuit had significant load served by a higher-voltage primary system with relatively low primary-side voltage drop. As we will see, distribution transformer and secondary issues limited the depth of voltage reduction.

II. Initial Aggressive Voltage Reduction

The initial LTC control settings were based on keeping the primary voltage above 118 V on the entire circuit. The minimum substation voltage is 119 V, based on keeping the primary above 118 V and adding 1 V to account for the controller bandwidth. At the minimum circuit load, there is no drop along the primary based on a planning powerflow circuit model. At peak load, there's a 3-V drop along the primary based on the powerflow model. Together, that gives a target substation bus voltage range between 119 and 122 V at minimum and peak loads.

For the line-drop compensation settings, we only used R and not X. This makes the controller insensitive to load power factor and to capacitor switching. With this *zero-reactance* method [3, 4], regulator settings can be found based on the minimum and peak loadings along with the circuit power factor and the regulator CT rating. With these inputs, the design settings were found as follows: V_{set} = 118.5 V, X_{set} = 0, and R_{set} = 4.5 V.

These settings were implemented on the reduced-voltage settings group within the regulator, and the day-on / day-off research control was initiated in the summer of 2009. Within one week of operations, a low-voltage complaint was received from a commercial customer. Site readings verified voltages were lower than expected.

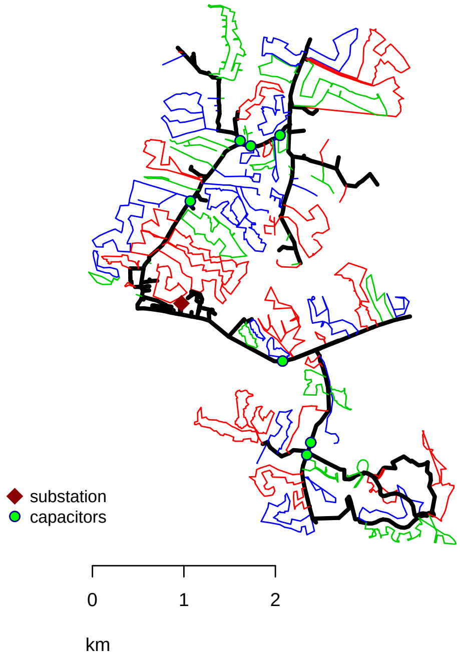

Fig. 1. 24-kV circuit with two feeders.

Manuscript received September 19, 2011. This work was supported by the Electric Power Research Institute (EPRI).

R. C. Belvin is with Duke Energy, Charlotte, NC, 28202 USA (704-382-2078, ron.belvin@duke-energy.com).

T. A. Short is with EPRI, Burnt Hills, NY, 12027 USA (518-374-4699; email: tshort@epri.com, t.short@ieee.org).

This commercial customer was near the substation. In response to an earlier high-voltage complaint, the no-load-taps on the customer's transformers had been changed to provide lower voltage. This customer had two transformers; one was changed to lower voltages by 2.4%, and the other was changed to lower voltages by 4.2%. If this was a long-term change and not a research project, these tap settings could have been changed back to the original settings. But, because this was a research project, and we needed to operate in normal mode and a reduced-voltage mode, changing taps was not an option. In order to raise voltages, LTC control settings were changed as follows: V_{set} = 121.6 V and R_{set} = 2.1 V.

Fig. 2 shows primary-side measurements on the circuit after the voltage control was first initiated. This graph shows measurements at the substation plus two additional points on each feeder. The feeder measurements were from potential transformers located at estimated low-voltage points near the ends of the circuit. The phases of each measurement are not necessarily the same. The circuit was in normal mode on Monday and Wednesday and reduced-voltage mode on Tuesday and Thursday (except for a short time on Tuesday).

Fig. 2 shows that the minimum primary design voltage of 118 V was not maintained during high load periods. It does not appear that the line-drop compensation increased the substation voltage as expected.

Fig. 3 shows voltage measurements from AMI from residential customers during the same time period. At each time slice, the lower 5, 50 (median), and 95th percentile meter voltages are shown. In both control modes, the meter voltages are generally within ANSI range A.

In retrospect, the initial voltage reduction settings were too aggressive. A staged implementation of increasing aggressiveness would have allowed review of the primary and secondary voltages to make sure there were no surprises. The lower-than-expected primary voltages combined with off-nominal distribution transformers led to the customer complaint.

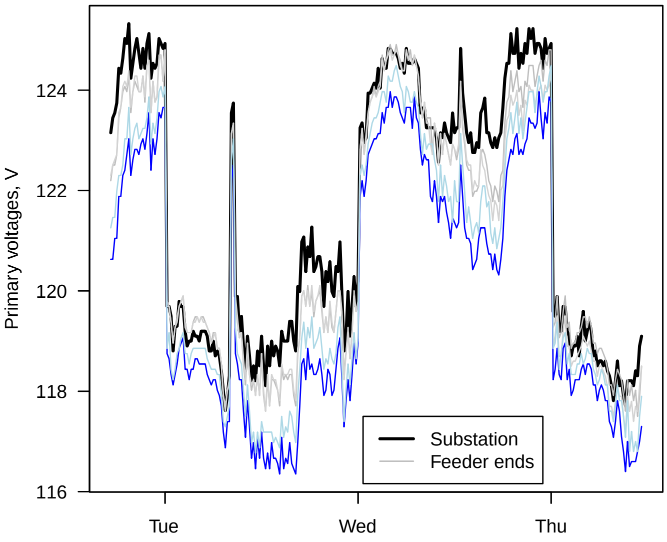

Fig. 2. Primary voltages based on initial controller settings.

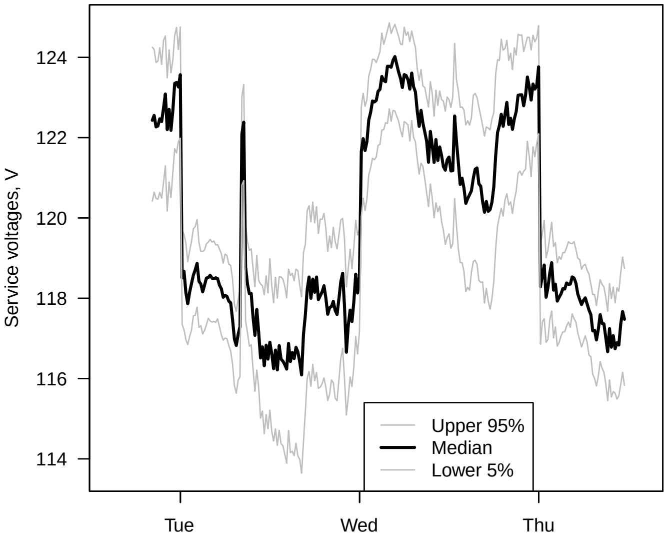

Fig. 3. Service voltages based on initial controller settings.

III. LONGER-TERM METER VOLTAGES

Once more conservative voltage control settings were used, primary voltages were relatively stable (see Fig. 4 and Fig. 5). Note that the distributions of meter voltages do not have the same shape in both control modes. The distribution of voltages during normal mode is flatter on the left side off the histogram in Fig. 4. The left tail of the normal-mode distribution is flatter meaning that there are more lower voltages relative to the overall average. Line-drop compensation during reduced-voltage mode likely explains this difference; in reduced-voltage operation, the line-drop compensation will boost voltages by raising the substation voltage at higher loads.

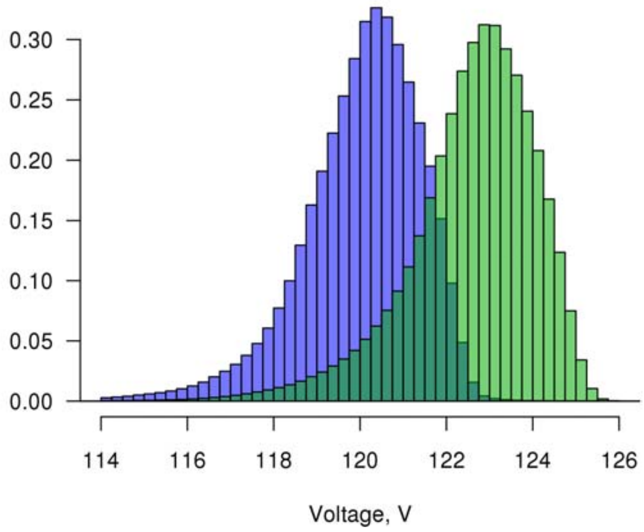

Fig. 4. Histogram of meter voltages.

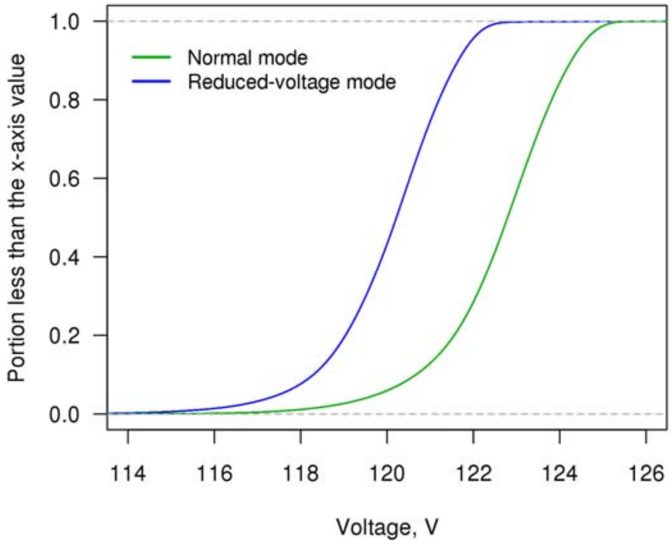

Fig. 5. Cumulative distribution of meter voltages.

AMI meters did measure a small percentage of voltage outliers. Fig. 6 shows a snapshot of meter voltages at peak summer load on one of the two feeders as a function of distance from the substation. The circuit was operating in reduced-voltage mode. Out of 2523 meters on this feeder, eight (0.3%) had voltages below 114 V (the lower ANSI range-A service voltage), and two (0.08%) had voltages above 126 V (the upper ANSI range-A voltage). Fig. 6 shows that the amount of voltage reduction is limited by a small number of meters. At peak summer load, only 2.8% of meters had voltages below 117 V. Circuits with little voltage drop on the primary are more forgiving of transformer and secondary issues. If these secondary issues can be addressed, the overall average voltage could be lowered by 2 to 3 V.

Fig. 7 shows a map that highlights the meter locations where voltages out of range A were measured. The low-voltage meters are scattered around the circuit. Field measurements of primary and secondary voltages were made to evaluate the cause of voltage outliers. Primary-side measurements confirmed that there was little voltage drop on the primary. Spot checks on secondaries showed a mix of transformer and secondary issues as the cause for low voltages.

The two meters with high voltages are on the same transformer; this transformer is likely on a wrong tap or had a design issue.

Note that no customer complaints were received once the voltage settings were changed. With AMI and near-continuous measurements, voltage outliers may be measured, where without AMI, these out-of-range voltages would have gone unnoticed unless a customer was particularly sensitive or voltages were extremely low.

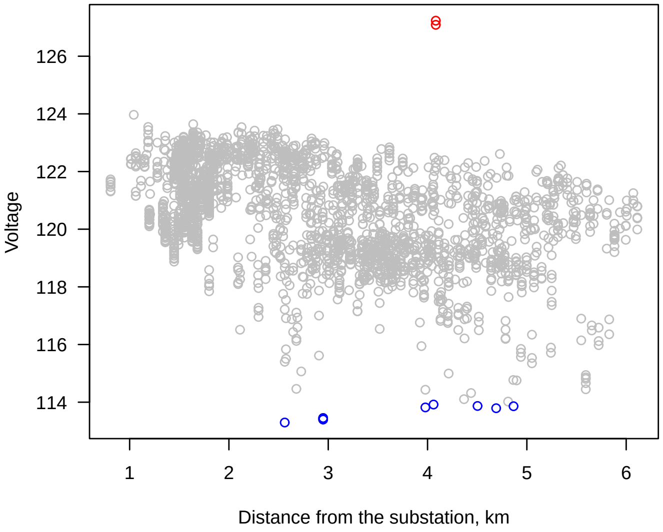

Fig. 6. Voltage profile of meters at peak load with outliers highlighted.

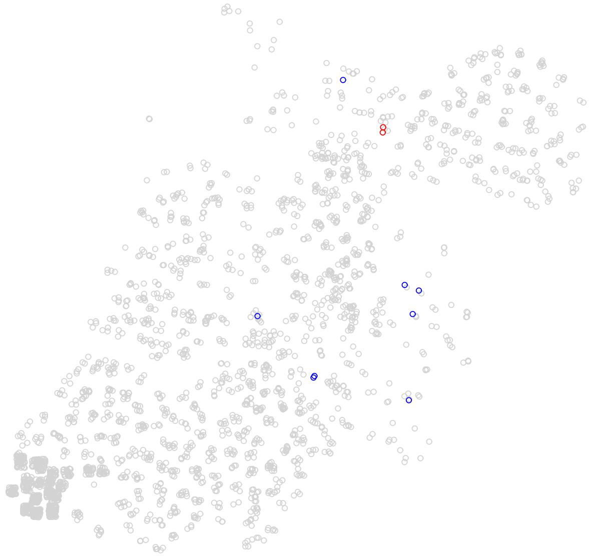

Fig. 7. Map of meters with outliers at peak load highlighted.

Fig. 8 shows another voltage profile graph for this feeder. Each point highlights the 99.9th percentile voltage (close to the peak voltage reading for that meter). Most of these near-peak measurements track the peak primary-side voltage and range from about 123.5 to 125.5 V. A small set of meters only sees near-peak voltages of between 119 and 120.5 V. Duke Energy has both 24.94 and 23.9-kV distribution circuits and transformers with both 14.4 and 13.8-kV (line-to-ground) primary-side voltages. The cluster of meters with low voltage was likely from application of 14.4-kV transformers on this 13.8-kV system, or that the transformer tap is on 14.4 kV rather than 13.8 kV. The ratio of 13.8 to 14.4 kV is 0.958. This ratio is on the order of the voltage seen by the small set of meters (0.958 × 125 V = 119.8 V). This set of meters accounted for less than 2% of the meters on the circuit. This set of meters does not explain all of the low voltages measured. Many of the other low voltages were from large loads on long secondaries.

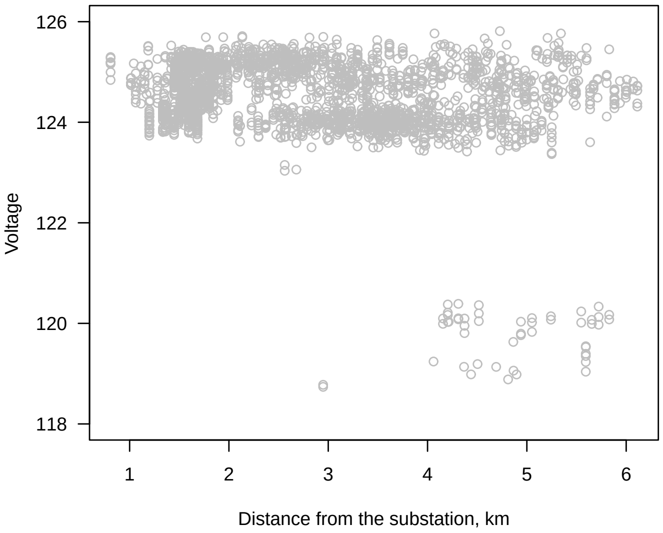

Fig. 8. Voltage profile of the 99.9th percentile meter voltages.

IV. DISCUSSIONS

As we have seen on this circuit, secondary-side issues on both residential and commercial customers can limit the depth of voltage reduction. The cost of upgrading secondaries or fixing transformer or secondary issues may need to be balanced against the benefit of additional voltage reduction.

On distribution transformers, taps and/or primary-side voltage ratings are an important consideration, especially for utilities that have different system voltages (for example 23.9 and 24.94 kV as in this case; 13.2 and 13.8 kV voltages are also common voltages that could get mixed up). Off-nominal taps or primary-side ratings can skew voltages and limit the amount that voltages can be reduced.

AMI can also reveal out-of-range service voltages that were unknown before implementation of AMI (many customers will not notice out-of-range service voltages).

Higher voltage distribution circuits and shorter circuits have stiff primary voltages that make them the best candidates for voltage reduction. These circuits with low primary-side voltage drop can mask secondary-side issues.

ACKNOWLEDGEMENTS

The authors wish to thank Kenneth R. Jordan, Distribution Planner, Duke Energy, for help in setting up and operating the field pilots. Ruth H. Neely, IT Project Manager, Duke Energy, also helped with AMI and SCADA data collection.

REFERENCES

[1] EPRI 1023518, Green Circuits: Distribution Efficiency Case Studies: Electric Power Research Institute, Palo Alto, CA, 2011.
[2] ANSI C84.1-1995, American National Standards for Electric Power Systems and Equipment -- Voltage Ratings (60 Hz).
[3] T. A. Short, Electric Power Distribution Handbook. Boca Raton, FL: CRC Press, 2004.
[4] General Electric, Omnitext, 1979.

Ron C. Belvin is currently the Director of Distribution Planning-Carolinas for Duke Energy based on Charlotte, NC. He has over 31 years of utility experience while working at Duke Energy. Mr. Belvin has a Bachelor of Science degree in Electrical Engineering from North Carolina State University (1980) and Masters of Business Administration from Queens University of Charlotte (2005). He is a registered Professional Engineer in North and South Carolina.

Tom A. Short 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.