LOAD MODELS FOR VOLTAGE OPTIMIZATION

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ABSTRACT

This paper describes the results of the EPRI Green Circuits and Load Modelling Initiatives and other individual utility tests to develop industry wide calculation procedures and model libraries. The paper presents standardized methods for estimating the impact of voltage management on electric distribution system operation.

INTRODUCTION

Voltage optimization is becoming an integral part of the distribution control strategy in the smart grid. Initial indications indicate a number of benefits from optimizing the distribution voltage profile. For many years, voltage reduction has been used as a demand management function in times of heavy demand. More recent research has shown that this can be part of the daily operation of the distribution system for both demand management and energy reduction. Conservation Voltage Reduction (CVR) may be one of the most cost-effective energy conservation measures that can be implemented. Despite the benefit potential, there are unanswered questions about how to estimate the actual energy savings and demand reduction that can be expected for different types of loads.

The paper will describe the problem of load model development from both the equipment perspective and the aggregated load perspective. It will identify definitions for customer classification so that voltage optimization benefits can be estimated with available information about customers and distribution systems. These aggregated customer load models will provide an understanding of how different types of equipment and even different models of equipment respond to voltage variations.

BACKGROUND

Management of distribution system voltage at the substation and along the distribution feeder has long been used to maintain service voltage within the limits set forth in industry standards, such as ANSI C84.1 in North America and EN 50160 (based on IEC 61000-3 standards) in Europe and other places in the world.

ANSI C84.1 specifies voltages in terms of “Service Voltage” and “Utilization Voltage” and also in terms of “Range A” and “Range B”. Each can be defined as follows:

- Service Voltage: The voltage at the point where the electrical system of the supplier and the electrical system of the user are connected.
- Utilization Voltage: The voltage at the line terminals of utilization equipment.
- Range A: Normal operational voltage range. Occurrence of voltage outside this range should be infrequent.
- Range B: Excursions of voltage above and below the Range A limits. While a part of practical operations, these excursions shall be limited in extent, frequency, and duration. Corrective action shall be taken to restore to Range A.

The specified limits are presented graphically in Figure 1. The significant differences in minimum service voltage and minimum utilization voltage are intended to account for drop in the customer’s premise wiring. The standards in Europe (EN 50160) and elsewhere use similar approaches for defining the range of voltages that need to be maintained at the customer interface.

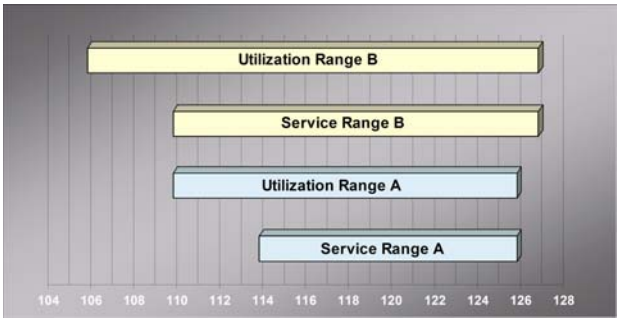

Figure 1
ANSI C84.1 Standard System Voltages

Conservation Voltage Reduction (CVR) refers to the management of service voltage for the purpose of reducing power and/or energy consumption. For many years utilities have used voltage reduction to reduce demand during periods of peak consumption. The practice of voltage regulation is now seeing renewed interest from utilities as both a demand management function and even for total energy use reduction.

One of the most thorough completed studies of the potential for CVR was the Northwest Energy Efficiency Alliance’s (NEEA) Distribution Efficiency Initiative (DEI). Complete reports of the findings from this study are available on their website. In addition, a Microsoft Excel based modelling tool that can help evaluate feeders for CVR is freely available at www.rwbeck.com/neea.

The EPRI Green Circuits initiative has significantly expanded this work by looking at the potential for energy savings and demand reduction on distribution circuits around the world. These evaluations are being performed as part of a comprehensive assessment of energy savings opportunities associated with each circuit being studied. The results are clearly showing that using CVR for energy savings can be one of the most attractive energy savings investments possible in terms of investment per kilowatt-hour saved.

The metric used to characterize the savings from voltage reduction is called the Conservation Voltage Reduction factor, or CVRf. CVRf is the percent reduction in load consumption divided by the corresponding percent reduction in voltage. A positive CVR factor indicates that a reduction in applied voltage results in a reduction in load consumption. The CVR factors measured during the NEEA's year-long Phase I DEI project are summarized in Table 1. This phase included two main projects – "Load Research" and "Pilot Demonstration." "Load Research" involved placing Home Voltage Regulators (HVR) on 500 homes. This allowed for the maintenance of minimum service voltage at every home, but was relatively expensive. It also limited the conservation benefits to those within the premises. The second part of the project reflected in the second row labelled "Pilot Demonstration" involved managing the voltage on 31 feeders from regulators at 10 substations. As indicated in the table, HVR allowed for more voltage reduction, but the CVR factor was higher for feeder regulation. Preliminary results from the Green Circuits initiative are in basic agreement with the results from the NEEA project.

Project	Voltage Reduction (ΔV)	CVRf (%ΔE/%ΔV)	Project Energy Savings (MWh)[1]	Percent Energy Savings
Load Research	5.2 V (4.3%)	0.569 [2]	87	2.15%
Pilot Demonstration [3]	3.03 V (2.5%)	0.69	8,476	2.07%

Notes:
1. Actual savings for DEI project (not annualized).
2. Based on random selection of residential sites, weighted to represent expected results for the Pacific Northwest Region.
3. Values are shown for the purpose of calculating the savings for project and do not represent expected values for the Pacific Northwest Region.

Table 1
CVR Factors from NEAA's DEI Project

VALUE OF LOAD MODELLING FOR VOLTAGE OPTIMIZATION

When evaluating CVR, it is common practice to assign typical CVR factors to their loads based on results reported by other utilities or by performing trial implementations of CVR on a small number of representative feeders. Basing widespread CVR implementation on the results achieved on other feeders may produce erroneous results. This is because considerable variation in actual results has been observed in the CVR factors on feeders that have been analyzed to date (Reference EPRI Green Circuits report). Figure 3 clearly shows this variation in CVR factor feeders studied.

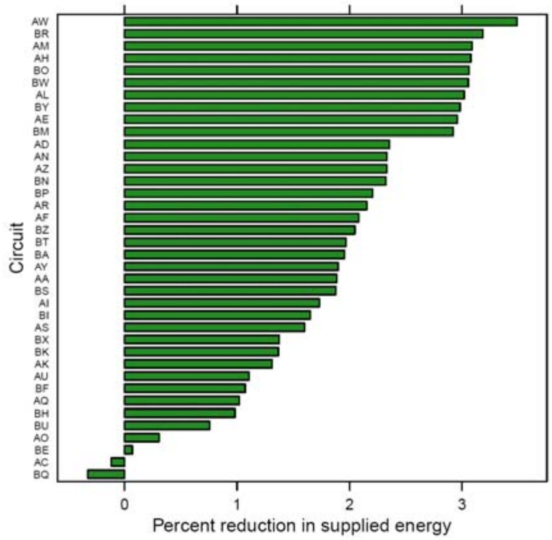

Figure 3
Variation in CVR Factor for Green Circuits Feeders

Some of the variation in CVRf between feeders can be attributed to the existing minimum voltage on some feeders being less than others, meaning that less voltage reduction is possible without violating minimum acceptable voltage limits. However, a significant portion of the CVRf variation can be attributed to having different loading characteristics on different feeders. Several studies, including EPRI Green Circuits, have shown the CVR factor varies seasonally and with time of day. Furthermore, the benefits that can be achieved using CVR will change over time because of increased voltage drop due to load growth and due to changing load-voltage characteristics of new end- use electrical devices that are being installed in increasing numbers on distribution feeders. Recent testing (reference PNNL report on CVR) indicates that the response of some new devices to voltage reduction can have significant impacts. In fact, some devices, such as LCD televisions, may have negative CVR factors (load actually increases when voltage is decreased. It is very important that electric distribution utilities that are contemplating using CVR as a mechanism for load reduction must be able to accurately predict the long range impacts of CVR.

The ability to predict in advance what the CVR effect will be through load modelling is important to electric distribution system managers, engineers and operators and other CVR stakeholders. For example, accurate CVR load modelling coupled with analytical tools that incorporate these models will:

- Enable long-range planners to determine whether CVR benefits will diminish with time. This is especially important to utilities that have deferred major capital expenditures for capacity additions (Reference Progress Energy CVR Project) based on expected CVR benefits.

- Enable operators to determine how much load reduction can be achieved at a given time using CVR during system emergencies
- Enable engineers to account for CVR operation when performing capacity planning studies.
- Enable engineers to determine the economic justification for making infrastructure improvements (such as “flattening” the voltage profile) to increase the CVR benefits
- Allow electric utilities to assign higher priority for CVR implementation to feeders that supply the maximum CVR benefit.

NEED FOR LOAD MODELLING INITIATIVE

To evaluate various distribution approaches for energy savings or demand reduction, electric distribution utilities must be able to accurately predict the energy savings and/or demand reduction that will be associated with the investment. The Green Circuits project has demonstrated that the modelling tools are available to evaluate the performance of the distribution system operation with different strategies for controlling the voltage. The unknown for evaluating the impact of CVR is the response of different types of loads to the voltage reduction.

If we are going to use CVR and voltage optimization as an important tool for managing load and achieving energy savings, it is necessary to justify this with accurate system models, including the response of the load. This requires addressing the modelling need from two different approaches:

- Understanding the fundamentals of equipment response. This involves understanding the voltage response characteristics of particular types of loads – lighting, motors, power supplies and other power electronic-driven loads, heating, etc.
- Understanding the aggregated response of loads. The important response at the feeder level is the overall response of groups of customers. This involves a combination of many types of loads.

The Load Modelling Initiative identifies important customer characteristics that impact the voltage response through testing at both the load level and the system level. This may be used to identify important customer categories that can be used for system models. This modelling effort helps the industry better integrate these customer categories and the associated voltage response characteristics as part of future utility customer information systems and distribution model databases so that they can be used as part of normal distribution planning studies in the future.

EPRI modelled the following end-use devices to determine the devices response to voltage reduction:

- Lighting (incandescent, CFL, LED, etc)
- Refrigerators
- Consumer electronics (PCs, monitors, television sets)
- Clothes washers/driers
- Dish washers
- Water heaters
- Heating and air conditioning
- Plug in electric vehicles
- Other significant end use loads

Where applicable, laboratory testing included various newer technology equipment, including the latest variable speed drive equipment.

POTENTIAL CVR SIDE EFFECTS

As CVR involves lowering the nominal voltage at the customer point of connection, end-use devices are directly affected. For residential or light commercial customers, the majority of loads are lighting, HVAC, water heating, refrigerators, and other power electronics that are not particularly sensitive to lower operating voltage. There is some possibility of increased tripping of in-premise circuit breakers. Specifically, this concern would relate to commercial or residential circuits that are running near capacity and serving loads that increase in current as voltage is reduced. Although such circuits arguably need attention anyway, this could potentially lead to more in-premise breaker trips.

Some adverse side effects of voltage reduction include:

- Slightly increased time for new technology lighting to reach full intensity
- Less lighting intensity during voltage reduction
- Slightly increased electric vehicle charging time
- Less reactive power delivered by primary voltage capacitor banks

An important aspect of the load modelling project is to identify important sensitivities of equipment to low voltage conditions. This information is expected to be of value in deriving optimum settings for voltage control systems as a function of the types of customers being supplied.

CUSTOMER CLASSIFICATION APPROACH

A customer classification system needs to be developed that is a compromise between the wide variations in response characteristics that can occur for different types of customers with different types of equipment and the availability of information about the individual customers.

Important characteristics that can be used for classification will be identified (customer size, geographic location, age of facility/residence, load profile characteristics, etc.) and a classification approach will be developed in cooperation with the members and the overall industry.

Important characteristics that were considered as factors for the customer classification include:

- Customer size
- Basic customer type (residential, commercial, small industrial, industrial)
- Age of facility/residence
- Load profile types (statistical assessment of load profiles as a basis for classification)
- Geography/region/climate
- Other characteristics

Note that it is important to address the customer voltage response characteristics over the whole year as part of this classification development process. The response to voltage changes may be significantly different for different types of customers in the summer but not in the winter (or the other way around).

CUSTOMER MODELS

A model structure was developed that can be applied across the different classes of customers to characterize the response to voltage variations. The models include consideration of the load vs. time impacts of the voltage variations as well as the demand impact so that the impacts on overall energy savings can be properly represented. For an aggregate load, this has been represented with a load representation that addresses the short term and long term statistical characteristics of how much load will be on at a given time in addition to the response of the load itself.

The load models will be verified based on a sampling of actual customers from the deployments selected for detailed analysis. The sampling approach was designed to provide appropriate response information across the important load characteristics identified in the previous task. Actual measurements of customer response across different seasons will be used as the basis for the model development. Additionally, voltage and consumption data for these customers will be analyzed in conjunction with the understanding of the types of devices within the facility and the related device testing results. Additionally, voltage and consumption data for these customers will be analyzed in conjunction with the understanding of the types of devices within the facility and the related device testing results.

MODEL VERIFICATION

The models developed based on detailed measurements will be verified and refined for use in actual planning and benefit assessment studies. A range of different distribution systems is expected to be selected for model verification at different levels of aggregation (transformer, feeder, distribution substation). The verification efforts are expected to take advantage of AMI deployments and other monitors as needed. The distribution systems selected will cover the range of seasons and climates, as well as customer types, and will to the extent possible, leverage detailed modeling work that has been conducted as part of the EPRI Green Circuits and PHEV Impacts projects. The customer modeling efforts and verification efforts will also be coordinated with other industry modeling initiatives.

For each of the distribution systems selected, a model verification effort will take advantage of extended measurements to verify the models in different seasons and conditions. These verification efforts will also build on measurements from ongoing deployments, such as distribution systems in the Green Circuits initiative.
Model refinements will be implemented based on the measurement results and a final library of models will be compiled for use in planning studies.