Evaluating Conservation Voltage Reduction: An Application of GridLAB-D: an Open Source Software Package

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***Abstract*—Conservation Voltage Reduction (CVR) is the reduction of energy consumption resulting from a reduction of the service voltage. While there have been numerous CVR deployments in North America, there has been little substantive analytic analysis of the effect; the majority of the published results are based on empirical field measurements. Due to the lack of analytic study, it is difficult to determine the impacts of CVR outside of sites that have conducted demonstration projects. This panel paper will examine a framework for the analysis of CVR using the open source software package GridLAB-D. An open source simulation environment is used to highlight the effectiveness of open source software programs and their ability to be used for evaluating multi-disciplinary smart grid technologies.**

***Index Terms*—Conservation voltage reduction, distribution system analysis, forward-backward sweep method, load modeling, Newton-Raphson Method, open source, power simulation, power modeling, smart grid.**

I. Introduction

The current generation of emerging smart grid technologies present complex multi-disciplinary problems that are difficult to evaluate using typical simulation tools. Emerging technologies such as demand response, distribution level energy storage, Plug-in Hybrid Electric Vehicles (PHEVs), and Conservation Voltage Reduction require simulations of not just the electric power system but also other disciplines such as building thermal models, financial market structures, communications networks, climate modeling, and battery chemistries. Typical simulation tools are designed to analyze single discipline problems and generally do so in an efficient manner; but the limitation of a single discipline limits their effectiveness for evaluating multi-discipline smart grid technologies.

Desktop simulation tools for electric power systems have become an indispensable tool for the modern engineer; this is true at both the transmission and more recently the distribution level. Tools such as General Electric's Positive Sequence Load Flow Software (PSLF) [1] and the Power World Simulator [2] are just two examples of the software packages that are available for the analysis of electric transmission systems. At the distribution level tools such as SynerGEE [3], WindMil [4], and Cymdist [5] are representative of the tools used for planning studies. These tools [1]-[5] are a small sample of the many simulation environments that have been developed for the analysis of electric power systems, a single discipline problem.

For the analysis of an electric power system, the consumption by an end-use customer, such as a commercial building, is treated as an input from an external source. The energy consumption can be determined by customer billing information, transformer loading information, or other estimates. This is appropriate if the building's impact on the electric power system is the primary focus of the study. If, on the other hand, the focus of the study is to determine how much energy a particular building consumes, then tools such as DOE2 [6], Building Loads Analysis and System Thermodynamics (BLAST) [7], and TRaNsient System Simulation program (TRNSYS) are appropriate. These tools [6]-[8] allow users to examine the energy consumption of different building designs with variations in parameters such as building square footage, wall and roof insulation, square footage of windows, and types of window coverings. Similar to the tools for the analysis of power systems [1]-[5], the tools of [6]-[8] are single discipline tools that are well suited to a specific purpose.

In addition to power systems and buildings models, many emerging smart grid technologies require the use of financial market structures and communication systems. As with power systems and buildings models, there are many tools that are effective at modeling these in an isolated manner. Financial market structures can be effectively modeled in connection with the transmission system using tools such as the AMES Wholesale Power Market Testbed [9] and the UPLAN multi-area model [10]. Communications systems can be modeled with the open source package NS-2 [11] and the new version NS-3 [12].

The tools from [1]-[12] are able to simulate their respective environments in an efficient manner, but their ability to model multi-disciplinary problems is limited. To model the multi-disciplinary problems presented by smart grid technologies, expertise from multiple disciplines is necessary. For example, the evaluation of a demand response scheme may require analysis of the electricity distribution system, the financial market structure, and the price responsive appliances. Each of these areas requires an expertise that is not often shared by the

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others. Specifically, few power engineers are experts at financial markets and smart appliance operations. Furthermore, with the exception of large research-oriented institutions, many organizations do not have staff members with the necessary wide range of expertise. Collecting experts from multiple, disparate fields and allowing them to collaborate in a single simulation environment is uniquely suited to the open source paradigm. GridLAB-D is one such open source simulation environment, and its ability to conduct analysis on smart grid technologies will be examined in this paper.

The rest of this paper is organized as follows: Section II discusses the GridLAB-D open source simulation environment, while section III discusses its open source distribution method. Section IV utilizes the GridLAB-D simulation environment to evaluate CVR. Section V contains the concluding remarks.

II. GridLAB-D Architecture

GridLAB-D is a multi-disciplinary simulation environment that can be integrated with a variety of third-party data management and analysis tools. GridLAB-D utilizes a multi-agent simulation engine including advanced algorithms that can determine the simultaneous state of millions of independent devices, each of which can described by differential and algebraic equations. By using a central control module to manage other agents in the system, GridLAB-D is able to integrate multiple modules into a single simulation environment, even if the individual modules use significantly different simulation methodologies.

The advantage of the multi-agent architecture over traditional differential-based solvers is that it is not necessary to integrate all the device's behaviors into a single set of equations. In addition to the core model, the GridLAB-D system also includes modules to perform the following functions:

- Power flow and controls, including distributed generation and storage
- Energy operations such as distribution automation, load-shedding programs, and emergency operations
- End-use appliance technologies, equipment and controls
- Data collection on object properties
- Consumer behavior including daily, weekly, and seasonal behavior profiles, price response, and contract choice
- Business operations such as retail rate, billing, and market-based incentive programs.

III. Open source Distribution

GridLAB-D was released as an open source simulation environment to a limited group of charter developers in December 2007. This release was the basis for the selected partners to develop modules proposed in response to a Program Opportunity Notice issue by the Pacific Northwest National Laboratory (PNNL) on behalf of the US Department of Energy (DOE).

Each of the subsequent releases of GridLAB-D have been made using SourceForge [13].

Since January 2008, collaborators have examined, tested and contributed to the GridLAB-D simulation environment through SourceForge. As new modules are validated, they are added to the standard release. Non-validated modules are available as add-ons from the open source repository, but are not installed as a part of the standard download available from the repository.

Under the Berkley Software Distribution (BSD) type open source license [14], developers are encouraged to create proprietary modules. Proprietary models can be managed so that sensitive information is not released into the open source. However, developers are required to distribute any unimproved GridLAB-D components free of charge, and provide prominent acknowledgement of the authors and funding used to create any proprietary modules.

IV. Conservation Voltage Reduction Analysis

The open source architecture of the GridLAB-D simulation environment has enabled researchers from multiple disciplines to collaborate in a unified frame work. The ability of an open source framework to enable the analysis of smart grid technologies will be shown via the examination of CVR on a set of radial distribution feeders that are representative of those seen in North America. This work would not have been possible without contributions from multiple disciplines.

A. Distribution Feeder Models

To conduct an evaluation of CVR, it is necessary to have a set of distribution feeders with which to conduct the analysis. Because of the critical infrastructure sensitivity of information regarding operational distribution feeders, actual feeder models were not appropriate for this work.

In an effort to address the need for openly available models that accurately reflect the distribution feeders used in North America, United States Department of Energy's (DOE) Modern Grid Initiative (MGI) developed a taxonomy of prototypical distribution feeders [15]. The feeders within this taxonomy were designed to provide researchers with an openly available set of distribution feeder models that are representative of those operating in the continental United States. The 24 distribution feeders within the taxonomy provide the relevant designed characteristics of distribution feeders without providing information about any specific feeder in operation; thus relieving the critical infrastructure concerns.

Because climate and energy consumption are closely coupled, the prototypical feeders within the taxonomy were divided into five climate regions based on DOE documentation providing design guidance for energy-efficient small office buildings [16]. The five climate regions, and their approximate divisions, are presented in Fig. 1.

Within each of the climate zones, there are a set of feeders that approximate the types of feeders that are seen within that zone. Table I gives a summary of the 24 prototypical feeders, including feeder name, base voltage, peak load, and a qualitative description.

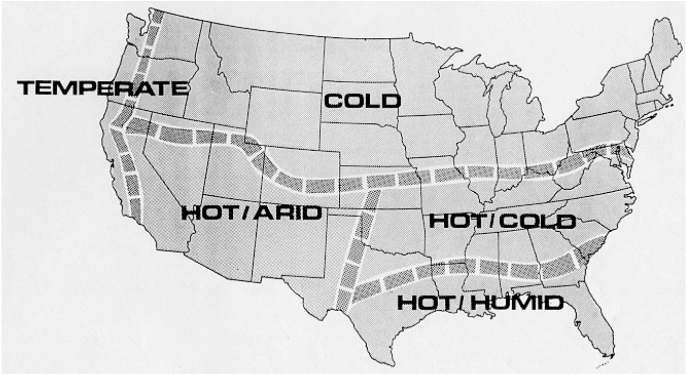

Fig. 1: Climate zones used for development of feeders

TABLE I
SUMMARY OF PROTOTYPICAL FEEDERS

Feeder	Base kV	Peak MVA	Description
R1-12.47-1	12.5	5.4	Moderate suburban and rural
R1-12.47-2	12.47	4.3	Moderate suburban and light rural
R1-12.47-3	12.47	2.4	Small urban center
R1-12.47-4	12.47	1.8	Heavy suburban
R1-25.00-1	24.9	4.9	Light rural
R2-12.47-1	12.47	2.3	Light urban
R2-12.47-2	12.47	6.7	Moderate suburban
R2-12.47-3	12.47	6.7	Light suburban
R2-25.00-1	24.9	4.8	Moderate urban
R2-35.00-1	34.5	21.3	Light rural
R3-12.47-1	12.47	6.9	Heavy urban
R3-12.47-2	12.47	11.6	Moderate urban
R3-12.47-3	12.47	4	Heavy suburban
R4-12.47-1	13.8	9.4	Heavy urban with rural spur
R4-12.47-2	12.5	6.7	Light suburban and moderate urban
R4-25.00-1	24.9	2.1	Light rural
R5-12.47-1	13.8	1	Heavy suburban and moderate urban
R5-12.47-2	12.47	10.8	Moderate suburban and heavy urban
R5-12.47-3	13.8	4.2	Moderate rural
R5-12.47-4	12.47	4.8	Moderate suburban and urban
R5-12.47-5	12.47	6.2	Moderate suburban and light urban
R5-25.00-1	22.9	8.5	Heavy suburban and moderate urban
R5-35.00-1	34.5	9.3	Moderate suburban and light urban
GC-12.47-1	12.47	12.1	Single large commercial or industrial

The prototypical feeders developed in [15] give an accurate representation of the physical infrastructure of the various distribution feeders from the substations to the customer meter at the residential, commercial, and industrial customers. To effectively evaluate CVR, the loads at each of the end-use customers must be modeled in adequate detail so that their voltage responsive behavior is accurate.

B. ZIP Load Models

One method of modeling end-use loads is with the traditional ZIP load model. The ZIP model is composed of time-invariant constant impedance (Z), constant current (I), and constant power (P) elements. Fig. 2 shows the circuit representation of the ZIP model [17]; the real and reactive power consumption of the ZIP model is given by (1) and (2). Equation (3) is a normalizing constraint for (1) and (2) that constrains the load model to consume rated power when at rated voltage.

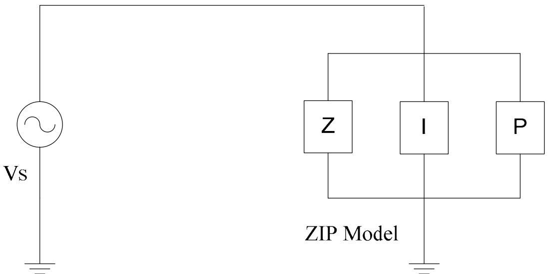

Fig. 2: The traditional ZIP model

$$P_i = \left[\begin{array}{l} \frac{|V_a^2|}{|V_n^2|} \cdot |S_n| \cdot Z_{\%} \cdot \cos(Z_\theta) + \frac{|V_a|}{|V_n|} \cdot |S_n| \cdot I_{\%} \cdot \cos(I_\theta) + \\ |S_n| \cdot P_{\%} \cdot \cos(P_\theta) \end{array} \right] \quad (1)$$

$$Q_i = \left[\begin{array}{l} \frac{|V_a^2|}{|V_n^2|} \cdot |S_n| \cdot Z_{\%} \cdot \sin(Z_\theta) + \frac{|V_a|}{|V_n|} \cdot |S_n| \cdot I_{\%} \cdot \sin(I_\theta) + \\ |S_n| \cdot P_{\%} \cdot \sin(P_\theta) \end{array} \right] \quad (2)$$

$$1 = Z_{\%} + I_{\%} + P_{\%} \quad (3)$$

where:
- P_i : real power consumption of the i[th] load
- Q_i: reactive power consumption of the i[th] load
- V_a: actual terminal voltage
- Vn: nominal terminal voltage
- S_n: apparent Power consumption at nominal voltage
- $Z_{\%}$: percent of load that is constant impedance
- $I_{\%}$: percent of load that is constant current
- $P_{\%}$: percent of load that is constant power
- Z_θ: phase angle of constant impedance component
- I_θ: phase angle of constant current component
- P_θ: phase angle of constant power component

The ZIP model is only appropriate for simple end-use loads that do not have control loops. Incandescent lights, compact fluorescent lights, liquid crystal displays, and oscillating fans are examples of loads that can be accurately represented by the ZIP model.

C. Multi-State Physical Load Models

Whether a load has a control loop or not, it must have the voltage dependent instantaneous power draw of a ZIP load. If the load does have a control loop, there is the added complexity of determining when the load is energized and for how long. If an end-use load has a control loop, it is necessary to have expertise in the process of the control loop, which is often outside the scope of typical distribution engineering.

One of the largest residential load types that has a control loop is Heating, Ventilation, and Air Conditioning (HVAC) systems. An equivalent thermal parameter (ETP) model is used to approximate the response of the electrical demand of the HVAC system as a function of solar input, temperature, humidity, voltage, and thermostatic set points [18]-[20]. The thermal parameters of the building are the mass of the building, which defines how much stored thermal energy is in the building, and the envelope, which defines how quickly the energy moves from inside to outside the building and can loosely be described as the insulation quality. These parameters are determined by the actual physical properties of the building, and include such values as floor area, ceiling height, aspect ratio, window types, air exchange rate, etc. Additionally, HVAC properties such as heating and cooling set points, heat type (gas, electric, or heat pump), fan power, motor losses, etc. can be defined. Fig. 3. is a diagram of the ETP model for a residential HVAC system.

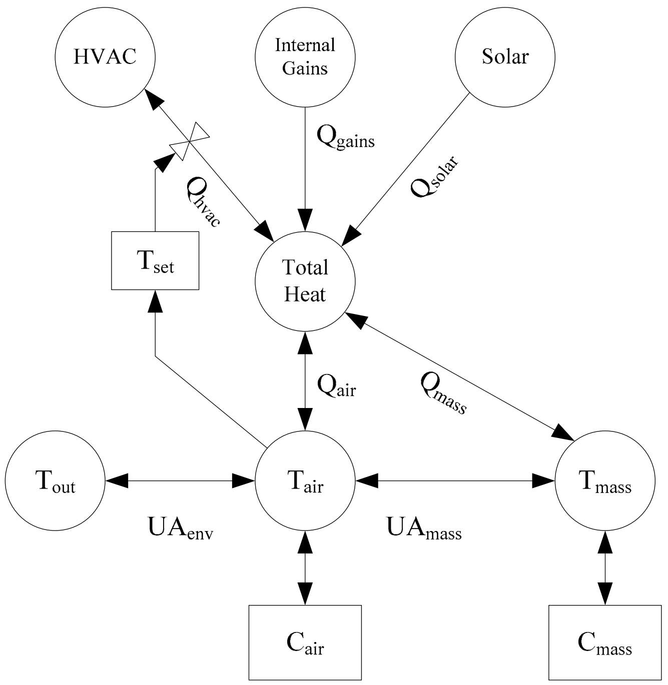

Fig. 3: The ETP model of a residential heating/cooling system

where,

C_{air}: air heat capacity (Btu/°F)
C_{mass}: mass heat capacity (Btu/°F)
UA_{env}: external gain/heat loss coefficient (Btu/°F-h)
UA_{mass}: internal gain/heat loss coefficient (Btu/°F-h)
T_{out}: air temperature outside the house (°F)
T_{air}: air temperature inside the house (°F)
T_{mass}: mass temperature inside the house (°F)
T_{set}: temperature set points of HVAC system (°F)
Q_{air}: heat rate to house air (Btu/h)
Q_{gains}: heat rate from appliance waste heat (Btu/h),
Q_{hvac}: heat rate from HVAC system (Btu/h),
Q_{mass}: heat rate to house mass (Btu/h), and
Q_{solar}: heat rate from solar gains (Btu/h).

Equation (4) is the second order differential equation that describes the heat flows shown in Fig. 3 [20]. The solution of (4) determines the time-varying temperature of the house, both air and mass, given the thermal inputs. With the inside air temperature, T_{air}, known, the thermal behavior of the heat pump system in response to the defined thermostatic set point, T_{set}, can be determined.

$$a\frac{d^2T_{air}}{dt^2}+b\frac{dT_{air}}{dt}+cT_{air}=d \tag{4}$$

where,

$$a=\frac{C_{mass}\cdot C_{air}}{UA_{mass}}$$

$$b=\frac{C_{mass}\cdot\left(UA_{env}+UA_{mass}\right)}{UA_{mass}}+C_{air}$$

$$c=UA_{env}$$

$$d=Q_{mass}+Q_{air}+\left(UA_{env}\cdot T_{out}\right)$$

To move the thermal energy between the two heat reservoirs, it is necessary for the electrical motor to provide the necessary energy. The electrical input energy to the motor, $S_{comp\text{-}motor}$, necessary to provide the thermal heat energy is a function of two elements: the heat flow through the cooling unit, Q_{hvac}, and the electrical losses of the compressor motor, S_{losses}, as shown in (5) [21]-[22].

$$S_{comp-motor}=\left[Q_{hvac}\left(T_{out},V_a,COP\right)+S_{losees}\left(V_a\right)\right] \tag{5}$$

The coefficient of performance (*COP*) is a scalar value that relates the cooling rate of the heat pump unit to the mechanical power delivered by the compressor. The COP is a measure of how efficient the cooling unit is. Additionally, it should be noted that Q_{hvac} is expressed in terms of British thermal units (Btu) consistent with the conventions of the heating/cooling industry in the United States and the derivation of the ETP model of [15]-[19], while S_{losses} is expressed in SI units. As a result, the two terms of (5) must be converted using the conversion of 1.0 Btu/h = 0.2931 W.

Utilizing the prototypical feeders populated with the appropriate combination of ZIP models and multi-state physical models, it is possible to develop accurate distribution feeder level models that provide the correct voltage response.

D. The CVR Control Scheme

CVR methods have been proposed in numerous academic papers and can be implemented through a number of commercially available voltage optimization schemes [23]-[31]. For the purposes of this panel paper, an openly published method of CVR was implemented [23]. The implemented CVR scheme was a dual objective system. The first objective switched the capacitors on the feeder to keep the power factor as measured at the head of the feeder as close to unity as feasible. The second objective utilizes remote voltage measurements to lower the voltage regulator tap positions to the lowest allowable values. The lowest allowable measurements on the primary distribution feeders were set to a 120V normalized value of 118V. This ensured that even with a 1V dead band, the voltage as measured at the customer's service meter was within the C84.1 Range A values of 114V-126V [32].

E. CVR Analysis

To evaluate the impact of CVR, each of the 24 prototypical distribution feeders was populated with ZIP models and full Equivalent Thermal Parameter (ETP) models for residential and commercial HVAC, which included their associated secondary distribution systems. The populated feeders were then simulated in a "traditional" voltage control scheme for an entire year at a 1-minute time step. The total energy consumed was then calculated for: the total feeder, the residential loads, the commercial and industrial loads, and the various system losses. Additionally, a set of End Of Line (EOL) voltages was recorded for each phase. The EOL points were determined based on the low voltage primary node at maximum system load. This voltage was then assumed to be the lowest voltage point on the system at any given time. The simulation was then rerun with the exact same feeders and load conditions, but with the CVR system operating. The difference in energy consumption was then examined. All simulations were run with a 1-minute time step for an entire year. Annual analysis at 1-minute time steps resulted in 525,600 time steps for each simulation. Each time step required the solution of not only the power flow problem, but the control problem for the CVR scheme, and the thermal solutions for the ETP models.

The two key benefits of CVR are peak load reduction and reduction in annual energy consumption. When the peak load is reduced, fewer generating units are required, especially costlier peaking units, while annual energy reduction requires less primary fuel to be consumed. Table II shows the peak load reduction and energy reduction for each of the prototypical feeders by percent.

While Table II only shows the percent peak load reduction and percent reduction in annual energy consumption, the complete analysis examined reduction in different load types as well as different loss types [33]. The values of Table II are given to highlight the ability of open source software, in this case GridLAB-D, to conduct detailed analysis on relevant problems facing the electric distribution industry.

TABLE II
PEAK LOAD AND ENERGY REDUCTIONS

	Reductions	
	% Peak	% Energy
GC-12.47-1	-2.14%	-3.96%
R1-12.47-1	-2.17%	-2.63%
R1-12.47-2	-1.06%	-2.01%
R1-12.47-3	-1.25%	-1.44%
R1-12.47-4	-2.16%	-3.88%
R1-25.00-1	5.63%	4.02%
R2-12.47-1	-0.10%	-1.53%
R2-12.47-2	-2.68%	-2.65%
R2-12.47-3	-1.16%	-0.62%
R2-25.00-1	-1.61%	-3.28%
R2-35.00-1	-2.28%	-4.35%
R3-12.47-1	-0.44%	-1.51%
R3-12.47-2	-1.30%	-2.06%
R3-12.47-3	-0.10%	-2.14%
R4-12.47-1	-1.95%	-2.38%
R4-12.47-2	-1.87%	-2.45%
R4-25.00-1	0.46%	-2.46%
R5-12.47-1	-0.83%	-2.06%
R5-12.47-2	-1.44%	-2.71%
R5-12.47-3	-0.34%	-1.54%
R5-12.47-4	-1.66%	-2.47%
R5-12.47-5	-0.69%	-2.10%
R5-25.00-1	-2.68%	-3.43%
R5-35.00-1	-2.33%	-3.65%

V. CONCLUDING REMARKS

This paper has shown that the existing generation of single discipline simulation tools is not adequate for evaluating the emerging generation of smart grid technologies. Open source collaborations, with their ability to bring together experts from multiple fields, offer one potential solution to this problem. As an example an evaluation of CVR was conducted with GridLAB-D, an open source simulation environment. Annual simulations were conducted with 1-minute time steps to evaluate the ability of CVR to reduce peak load demand and annual energy consumption. Simulation results were obtained that are consistent with industry experience from field demonstrations. These results show that open source software has a strong role to play in the evaluation of emerging smart grid technologies.

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VII. Biographies

Kevin P. Schneider (M'06, SM'08) received his B.S. degree in Physics and his M.S. and Ph.D. degrees in Electrical Engineering from the University of Washington. His main areas of research are distribution system analysis and power system operations. He is currently a research engineer at the Pacific Northwest National Laboratory, working at the Battelle Seattle Research Center in Seattle Washington. Dr. Schneider is an Adjunct Faculty member at the Washington State University, an Affiliate Assistant Professor at the University of Washington, and is a licensed Professional Engineer in Washington State. He currently serves as the Vice-Chair for the Seattle Power Engineering Society section and as Vice-Chair for the IEEE Distribution System Analysis Sub-Committee.

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David P. Chassin (M'03, SM'05) received his B.S. of Building Science from Rensselaer Polytechnic Institute in Troy, New York. He is a staff scientist with the Energy Science and Technology Division at Pacific Northwest National Laboratory where he has worked since 1992. He was Vice-President of Development for Image Systems Technology from 1987 to 1992, where he pioneered a hybrid raster/vector computer aided design (CAD) technology called CAD Overlay™. He has experience in the development of building energy simulation and diagnostic systems, leading the development of Softdesk Energy and DOE's Whole Building Diagnostician. His recent research focuses on emerging theories of complexity as they relate to high-performance simulation and modeling in building controls and power systems and is currently responsible for the design and development of DOE's GridLAB-D simulator.