Cost and Benefits of Volt-Var Optimization on Electric Power Distribution Systems: An Undergraduate Research Experience

Abstract:

This paper presents the results of an interdisciplinary undergraduate research project that investigated the economic cost and benefits of implementing Volt-VAR optimization (VVO) on distribution feeders with an emphasis on the Pacific Northwest region. The team comprised of two undergraduate students, an electrical engineering faculty adviser, and engineers from a local utility. Volt-VAR optimization is the combination of both conservation voltage reduction (CVR) and volt-ampere reactive (VAR) optimization. The goal of CVR is to reduce energy consumption by lowering the voltage magnitude toward the lower limit of the ANSI C84.1 range (i.e., 114 V). This scheme uses end of line (EOL) measurements to control the substation voltage regulators so that the appropriate voltages are set. To implement VAR optimization, utilities switch shunt capacitors onto distribution system feeders to reduce the amount of power losses resulting from reactive power flow. Implementing both CVR and VAR optimization in tandem by using advanced communication and control schemes comprise the complete VVO system.

Time series data were collected from simulations conducted using GridLAB-D software at step sizes of 1 minute for an entire year. Traditional loads on the distribution system were modeled using the static ZIP model, whose weights were determined through a least squares fit. Thermostatically controlled loads were modeled using the equivalent thermal parameter (ETP) model. Finally, a composite model was developed by combining the two different types of loads that appear on a distribution system to develop a representative building load. The loads were then aggregated together, and through the law of large numbers, appear identical to the actual behavior of loads on a distribution system. The relative weights of different loads were varied until they were found to match that of actual supervisory control and data acquisition (SCADA) data. Simulations on 24 prototypical distribution feeders were performed using GridLAB-D, both with and without VVO, and the resulting energy consumption was analyzed. Estimation for the economic costs and benefits of VVO in the Pacific Northwest was done by combining simulation data and past survey data from the Snohomish PUD. Energy cost savings are then converted to dollar amounts using market rate electricity prices for each region (i.e., typically 10 cents per kWh).

The challenges, opportunities, and student experiences of this research is also presented. Two students worked on this project over the course of three months in the summer. As the nature of this research was interdisciplinary, it required significant cross-collaboration as well as background knowledge in both engineering and economics. The students performed extensive literature review on these topics before reaching out to the engineers from local utilities for guidance. The results of this research is highly beneficial to the students as well as to the utility. Along the way, the students develop communication, project management, and soft skills that will serve them well into their professional careers.

1.0 Introduction

As demand for energy increases across the United States, generating electricity from clean and reliable sources becomes more challenging for utilities. One solution that utilities have been investigating is Volt-VAR optimization (VVO), which manages voltage levels through conservation voltage reduction (CVR) and reduces energy losses by controlling reactive power flow [1].

The purpose of CVR is to conserve energy by slightly reducing the voltage that customers receive without affecting the performance of the devices it serves [2]. During initial pilot projects of CVR in the 1970s, utilities such as Snohomish PUD reported great success in reducing the amount of energy consumed per household. They observed a direct correlation between lowering the voltage and lower energy demand [3]. However, as the energy crisis subsided in the late 1980s, many utilities ended their CVR programs.

Utilities also reduce energy losses through volt-ampere reactive (VAR) optimization. A typical distribution system has power losses ranging from 3% to 9% due to transformer losses, conductor resistance, and VAR losses [4]. To reduce these losses, utilities install shunt capacitors on distribution feeders or substations. Today, utilities manage both voltage levels and reactive power flow simultaneously by utilizing new communication and control technologies. When utilities manage and optimize both voltage and reactive power simultaneously, it is referred to as Volt-VAR optimization (VVO) [5].

This report presents the results and experiences of undergraduate researchers who investigated how VVO can be implemented for utilities in the Pacific Northwest region. Load characteristics specific to the Pacific Northwest are examined as they relate to VVO.

1.1 History of Voltage Regulation

Beginning in the early 2000s, the Pacific Northwest led the country in voltage regulation research and development. Utility Distribution System Efficiency Initiative (DEI) was a program funded by the Northwest Energy Efficiency Alliance (NEEA) in which utilities, such as the Snohomish PUD and Puget Sound Energy, were tasked to increase distribution efficiency through implementation of CVR. Research suggested that CVR provided energy savings and a reduction in peak demand but development came to a halt due to lack of funding [3].

A report about the effects of CVR on a national level was published by the Pacific Northwest National Laboratory (PNNL) in 2010. The study found that implementing CVR on every distribution feeder in the United States will provide a 3.04% reduction in annual energy consumption. In 2017, the total electricity demand of the United States was 4.01 trillion kWh; therefore, a savings of 3.04% would reduce electricity consumption by 121 billion kWh, enough to power 11 million homes [1]. With the average U.S. household consuming 10,764 kWh of electricity per year, a savings of 3.04% on electricity would result in a reduction of electricity consumption by 327 kWh per year.

Since 2009, the Pacific Northwest Smart Grid Demonstration Project (PNSGDP) has researched into the barriers to implementing VVO in the Pacific Northwest region. The goal of this project is to validate new Smart Grid technologies, implement two-way communication techniques, quantify their costs and benefits, and improve interoperability [3].

2.0 System Load Modeling

Loads connected to the power system consumes both active and reactive power. Utilities use load models to predict the behavior of loads when subjected to a change in voltage. In most cases, loads are modeled in aggregate because representing the individual load of every device on a system is impractical [6]. There are two types of loads and they differ in response to when the voltage is reduced: loads without a thermal cycle and loads with a thermal cycle. Loads without a thermal cycle are traditionally modeled using the constant impedance, constant current, and constant power (ZIP) model. The relative ratio of constant impedance, current, and power varies depending on the actual load. For example, Table 1 shows. For example, Table 1 shows the relative ratios for the ZIP models of some typical household appliances [1].

Table 1: Appliance ZIP model ratios [1].

Appliance	**Z (%)**	**I (%)**	**P (%)**
Plasma TV	-32.1	48.3	83.7
Incandescent Light	57.1	42.6	0.3
Fan	73.3	25.3	1.4

Loads with a thermal cycle have an additional control loop which determines the time and duration in which the load is energized. For example, a thermostatically controlled water heater may draw less instantaneous power in response to voltage reduction, but remains on for a longer period of time to complete its functionality, thereby using the same amount of energy. In this case, the thermostatically controlled end-use load does not provide any energy reduction benefit, but does reduce peak energy demand [7]. Figure 1 shows a representative load cycle for both a load with a thermal cycle (Fig.1(a)) and a load without a thermal cycle (Fig.1(b)). Other appliances that are thermostatically controlled include heating, ventilation, and air conditioning (HVAC) units.

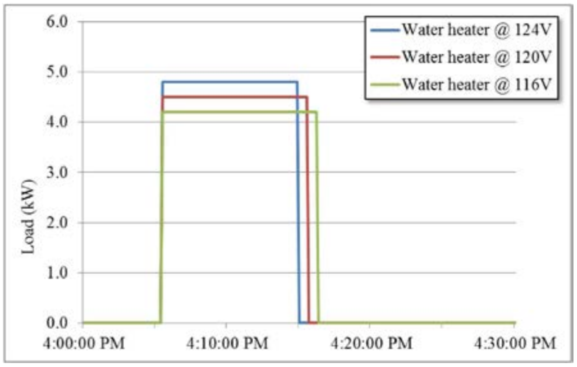

Figure 1(a). Load with thermal Cycle.

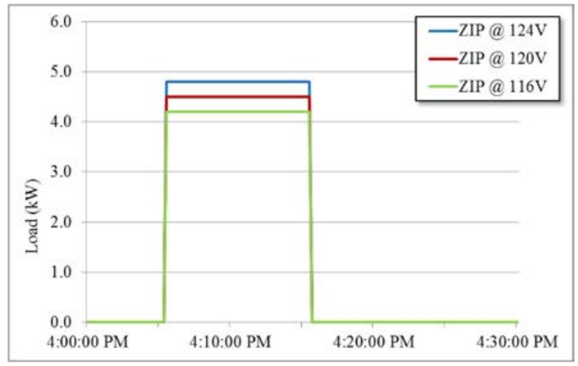

Figure 1(b). Load without thermal Cycle.

Figure 1. Comparison of loads [8].

3.0 Volt/VAR Optimization

Volt/VAR Optimization (VVO) is implemented through voltage regulation and reactive power control to achieve the operating objective of minimizing losses and power demand. If voltage and reactive power control are integrated together, then the costs of operation are significantly reduced [9]. What differentiates modern VVO techniques from traditional approaches is the use of integrated monitoring and communication systems. In the past, utilities would manage voltage regulators and VAR compensation devices independently, which would be suboptimal on feeders, substations, and the distribution system. Advances in infrastructure and software have allowed VVO to become a major resource for utilities in implementing energy efficiency improvements.

3.1 Conservation Voltage Reduction

Conservation voltage reduction (CVR) is the planned lowering of the voltage magnitude on distribution circuits with the goal of reducing load demand and energy consumption, especially during peak load periods. In the United States, the American National Standard for Electric Power Systems and Equipment – Voltage Ratings (ANSI C84.1-2011) requires primary distribution circuits to maintain a voltage within a specific range of values [10]. For residential customers, the voltages are required to be within the range of 114V to 126V. Figure 2 shows the distribution voltage profiles with and without CVR.

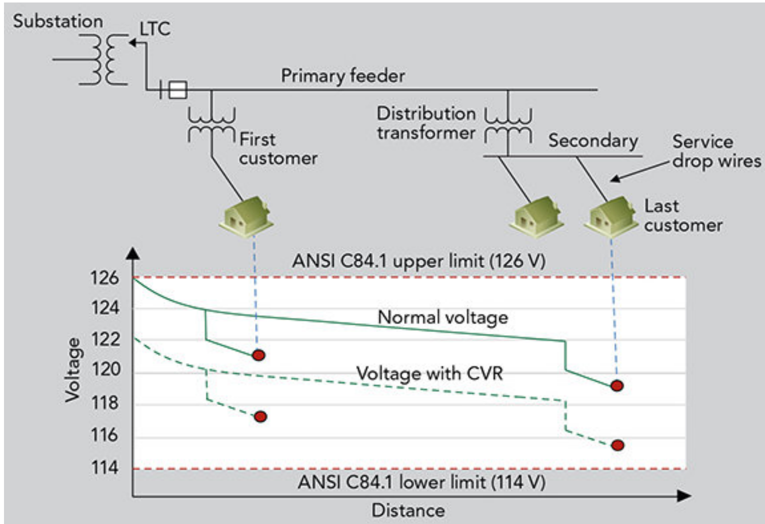

Figure 2. CVR overview [2].

Table 2 lists some of the common devices power system operators use to control voltages and reactive power. Many loads consume less energy in response to a reduction in the voltage level. As a result, these loads are subjected to less wear and tear, ultimately increasing their life expectancy.

Table 2: Equipment for voltage support and reactive power control [16].

Equipment	**Grid Location**	**Function**
Load Tap Changer	Substation transformers	Adjust feeder voltage at substation
Voltage Regulators	Distribution feeders and substations	Adjust feeder voltage at substation or along feeder
Capacitor Banks	Distribution feeders and substations	Reactive power compensation and voltage support

Utilities characterize a device's response to voltage level reduction through the load-to-voltage sensitivity factor, also known as CVR factor, which can be computed as:

$$\text{CVR factor} = \frac{\%\Delta E}{\%\Delta V} \qquad (1)$$

where %ΔE is the percent change in power demand and %ΔV is the percent change in voltage. This parameter measures the percentage of load reduction with respect to the percentage of voltage change; it measures the effectiveness of voltage reduction in reducing energy consumption. Every electrical appliance has a specific CVR factor, which is mainly determined by its load behavior. The aggregate CVR factor depends on the customers' load mix, transformers, conductor characteristics, and other devices connected to the distribution system [8].

The most common types of loads in a power system are constant impedance and constant power loads [11]. The CVR factor for constant impedance loads tends to be higher than constant current and constant power loads. Constant power loads have a near zero CVR factor since their energy consumption is independent of the voltage level. Figure 3 shows the CVR factor for some common consumer appliances. Most consumer appliances have at least a CVR factor of 50%.

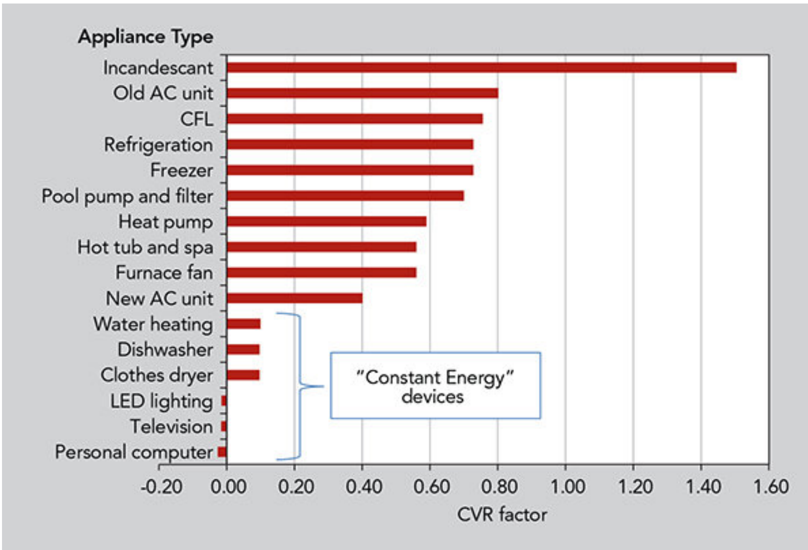

Figure 3. CVR factor of common appliances [2].

3.2 VAR Optimization

The vast majority of loads on the distribution system are inductive, which causes the current to lag the voltage, resulting in a positive power factor angle and reactive power generation. A large amount of reactive power incurs additional costs for both the utility and customer [4]. In order to reduce the amount of reactive power flow, utilities switch in shunt capacitors from large capacitor banks at substations.

Utilities can now control voltage and VAR levels together in a coordinated manner to optimize power flow. Advanced metering infrastructure (AMI) and geographic information systems (GIS) provide the utility with a much greater precision in monitoring and controlling voltages. The AMI provides a two-way communication between the smart meter and the utility company. The information collected includes real-time data on power consumption across the grid. Utilities create voltage maps of their service region using GIS software and AMI data to identify locations experiencing voltage issues and resolve them in real-time [12].

4.0 Analysis of VVO Results

Through collaboration with engineers from a local utility, research was done on how VVO technology can impact the electrical power distribution system in the Pacific Northwest region. A full evaluation of VVO is complicated by exogenous factors such as environment, customers, regulatory requirements, and financial costs. One way to analyze the effects of CVR on a Pacific Northwest distribution system is to examine the types of loads that are used most often by the typical end-user in the area. The Pacific Northwest's coastal climate features relatively cool summers and cold winters. Throughout the United States, the biggest electrical load for residential customers is usually air conditioning. Due to the temperate climate of the Pacific Northwest, air conditioning cost accounts for only 2% of the home energy expenditure, compared to the national average of 12% [13].

Most Pacific Northwest utilities prioritize infrastructure (i.e., improving feeder "health") over introducing new capital projects onto the grid. Navigant research conducted a study with a group of thirty Pacific Northwest utilities regarding distribution efficiency [3]. When utilities were asked about barriers to improving their distribution system, respondents overwhelmingly reported that access to capital and cost-effectiveness of VVO were the biggest challenges. Utilities were also surveyed on ways to overcome these barriers and implement VVO technologies. Government regulation, legislation, and incentives were the most common solutions provided. Incentives and regulations such as I-937, funding from DOE's Smart Grid Investment Grant (SGIG) program, and BPA's Energy Smart Utility Efficiency (ESUE) program are major driving factors behind Pacific Northwest utilities' development of VVO [3].

4.1 Local and National Results

Although the overall CVR factor for each utility's load vary, most find a 1% to 3% energy savings, 2% to 4% peak demand savings, and 4% to 10% reactive power reduction with deployment of CVR [3]. In a 2014 study, Snohomish PUD found that the average CVR factor for their utility region is 0.70, which is shown in detail in Figure 4 [14].

Snohomish PUD estimated that a typical feeder will have energy savings of 140,000 kWh per year by implementing CVR. The utility concluded that it is an effective and viable method to reduce energy consumption, and costs less than $0.010/kWh to implement [14].

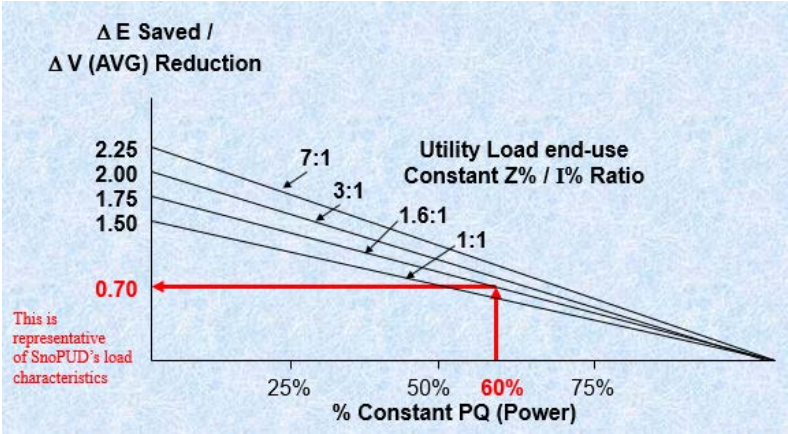

Figure 4. Snohomish PUD's average CVR factor [14].

In the value chain (i.e., generation, transmission, distribution, and end-user), the distribution bears all the costs of implementing VVO. Approximately three-quarters of the benefits that Pacific Northwest distribution utilities receive from VVO come from avoided capacity costs to the grid [15]. Utilities can avoid additional capacity because VVO reduces peak energy consumed.

In PSE's 2017 Integrated Resource Plan (IRP), CVR is determined to be a useful resource in reducing energy cost for end users without damaging any appliances [16]. The company has been researching CVR's advantages and disadvantages since 2006. Through a pilot study of 10 residential customers, PSE concluded an average of 2% energy savings for residential customers who have access to this technology.

5.0 Student Experience

This project was funded by a grant from the Snohomish Public Utility District with the goals of 1) providing an opportunity for students to perform interdisciplinary research and have experience collaborating with industry partners and students outside of their major and 2) gathering meaningful research data that has real societal impact. Studies have shown that in order for such industry-academic partnerships to be successful, the project must be clearly defined with a uniform team vision. Effective and regular communication links must be established. Commitment from both parties are crucial for the overall success of the project [17]. On the other hand, previous research has reported challenges that prevent effective industry-academic collaboration. These include lack of trust, issues related to intellectual property rights, time constraints, and differences in expectations [18].

Prior to the start of the project, the faculty reached out to industry to solicit suggestions of research that is suitable for undergraduate students to complete within four months yet also meaningful and stimulating. Within the university, the faculty contacted students enrolled with the Institute for Energy Studies to discuss this opportunity. After interviewing multiple candidates, two non-engineering students were selected on the basis of availability, course performance, and interest. They were paid a summer stipend to work on this research.

During the execution of the project, there were weekly meetings with the faculty adviser as well as group presentations and discussions with other engineering students. The students working on the project were encouraged to communicate and discuss their results with other faculty who have research areas aligned with this work and industry collaborators. The students who worked on this project found the cross-disciplinary nature of the research to be especially rewarding given the challenges. Much of the engineering background knowledge needed for this project was obtained through literature review and then reaching out to the engineering students and engineers from the local utilities. The faculty provided the contact information and the bridge for the students to reach out to the appropriate people.

With such interdisciplinary projects, no one member held all of the knowledge needed to answer the questions posed. By collaborating with others, the students also learned project management, communication, and research skills, which are all important for their future career. One student commented:

"I made connections and learned new skills that will help guide me toward further success in my future research endeavors. In each department that I worked with, I was able to obtain information on topics I was not yet familiar with. For example, in the engineering department I was introduced to concepts pertaining to the science behind VVO. Every week I would meet with other students within the energy department and we would discuss our research projects. During this time, I was able to receive helpful feedback from other students regarding my paper. We were able to share ideas, connections, and resources that ultimately helped improve our research." – WWU student

This was also the first time the student communicated with professional engineers from the local utilities. Their guidance allowed the students to see the practical nature and the benefit of their research, as this information is helpful for the local utilities in their system planning.

Finally, the students reported their writing ability greatly improved from this experience.

"My confidence in my writing was also improved due to the amount of editing and feedback that I was given throughout the project. For future projects and papers, I plan to use my developed skillset to complete work more efficiently, and with better quality." – WWU student

6.0 Conclusion

Nearly every study done on VVO in the Pacific Northwest has concluded that VVO has a positive impact on the distribution system. The impact of VVO on a distribution system leads to cost savings for both the utility and the customer while also improving the reliability of the energy supply. The challenges that utilities face when upgrading the efficiency of their distribution systems include access to information regarding the cost-effectiveness of technologies, access to capital, and availability of funding for additional pilot projects.

The next step in evaluating the economic cost and benefits of VVO in the Pacific Northwest is to focus on rural utilities' distribution systems. Evidently, VVO is a valuable resource for improving the efficiency of a distribution system, but most studies have focused on the more populated, urban locations where access to capital is more readily available. Utilities that serve rural areas usually have a distribution system that is more outdated, hard to reach, and fewer sensors to gather data for VVO. Policy, economical, and technological factors all need to be carefully examined before VVO can be deployed in rural areas of the Pacific Northwest.

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