

Load Modeling and Voltage Optimization Using Smart Meter Infrastructure

Bimal Shah, Anjan Bose, Anurag Srivastava
The School Of Electrical Engineering and Computer Science,
Washington State University
Pullman, WA
bimal.shah@email.wsu.edu

Abstract—Voltage – Var Control and Optimization (VVC&O) mechanism in distribution system assisted by local controllers and Distributed Management System (DMS) helps in meeting operating criterion and achieving energy savings. Conservation Voltage Reduction (CVR) with VVC&O allows reduction in peak load and energy consumption, by having flat voltage profile near lower bound of ANSI Standards (114V), while maintaining power factor within limit. To estimate the energy saving, CVR factor is needed and accurate load modeling is required to estimate CVR factors. In this work, distribution system was modeled and simulated utilizing data from one of the feeder in Pullman, WA. This paper presents the results of the study done on improving the VVC capabilities by integrating Smart Meter Infrastructure. Load Modeling was done by observing the behavior of loads at each house and comparing the smart meter data with the simulation results. Precision of developed load model provides enough information to make a decision on required changes in voltage at a substation at a given time for energy saving without violating operation criterion. Results of VVC&O show that energy saving of 4-5% can be achieved at the typical distribution substation.

Index Terms—Conservation Voltage Reduction, Energy Savings, Load Modeling, Peak Load Reduction, Smart Metering Infrastructure, VVC&O (Volt-Var Control and Optimization)

I. INTRODUCTION

Efficiency of Electric Power Distribution System (EPDS) is critical in designing sustainable power grid infrastructure. Automation in the distribution system allows utilities to implement flexible control of distribution systems to enhance efficiency, reliability, and quality of electric service.

To estimate energy saving and get better situational awareness of EPDS, it is necessary to get measurements at strategic locations and estimate the load characteristics. As part of smart grid initiative, smart meters were installed for better monitoring and possibly control end user loads. Analyzing these massive set of collected smart meter data for

useful tasks has its own challenges. Modeling of EPDS including load models is necessary to use these measurements for specific smart grid goals. For load modeling, several research approaches were developed like least square optimization, regression analysis to calculate ZIP (constant impedance, constant current and constant power) parameter and Conservation Voltage Reduction (CVR) factor [1]. This approach may not work, since all the loads are not always static or time-invariant. So we may not get accurate CVR factor for the particular feeder.

In this paper, we classified load Models into two broad categories: static and dynamic. Static model are ZIP load with combination of constant impedance, constant current and constant power loads while dynamic model has time series simulation of end user loads mainly HVAC (Heating Ventilation and Air Conditioning) and water-heater. This paper focuses both on static as well as dynamic load models since we are trying to do voltage optimization using Distribution Management System (DMS) and smart meter data. Analysis in this paper utilizes a typical feeder from Avista Utility in northwest USA. It was assumed that utility wants to have voltage at primary side of distribution transformer to be at 120V [2] and power factor to be above 0.95 lagging.

This paper uses actual real time data at 5 minute interval provided by the utility for one of the feeder and comparing that real time data to the simulation results in GridLAB-D [3]. Once the comparison of real time data and simulation results are in reasonable range we can divide the loads into number of houses and run the simulation to record the individual house data. Now the goal is to compare the simulation results with the Smart Meter data available from the utility. The procedure is explained in detail for load modeling in section III.

The rest of paper is organized as follows: section II gives brief information on the feeder and exporting feeder model from Synergie [4] to GridLAB-D. Further, load modeling concept is explained in section III followed by Volt-Var control scheme implementation in section IV. Section V combines Volt-Var control scheme and load modeling to validate load model based on real time DMS and Smart Meter Infrastructure (SMI) data provided by the utility. Last section

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VI has concluding remarks on the contributions and findings of this research work.

II. DISTRIBUTION SYSTEM

Avista Utility has successfully installed number of smart devices and over 13000 smart meters in Pacific Northwest, Pullman, WA [5]. One of the goals is to achieve annual energy saving by reducing the feeder voltage within the range of ANSI Standards 114V-126V without affecting end user customers and hence improve the efficiency and reliability of EPDS. Smart meters provide voltage and power consumed and has been used in this paper to make the end user model more accurate. There are total of 13 feeders in Pullman, WA with smart meters and of the feeder-1 (F-1) has been used in this study for load modeling and voltage optimization as shown in figure 1.

A. Exporting feeder model from Synergiee to GridLAB-D:

Figure 1 shows the graphical representation of the feeder in Synergiee. Feeder information was provided by utility in database and model form in Synergiee. Synergiee is distribution software by Stoner Electric with capability of simulate, analyze and plans power distribution feeders, networks and substations. Avista uses Synergiee as distribution tool for distribution system analysis. Model is exported to GridLAB-D, which is open source distribution module developed by Pacific Northwest National Laboratory with capability of detail end user load modeling. GridLAB-D is the tool that has combination of distributed automation along with high performance algorithm. Load Flow results were compared between both the software tools for validation.

B. Load Flow Analysis and Results:

A distribution system generally originates from the substation where electric power is converted from high voltage to lower voltage for delivery to customers. Usually, a distribution system has a radial topological structure. There are two primary requirements for analysis: a. modeling must reflect the actual behavior of the system components. b. the solution algorithm must be robust and efficient. In this work, Newton Raphson method was chosen to solve the power flow

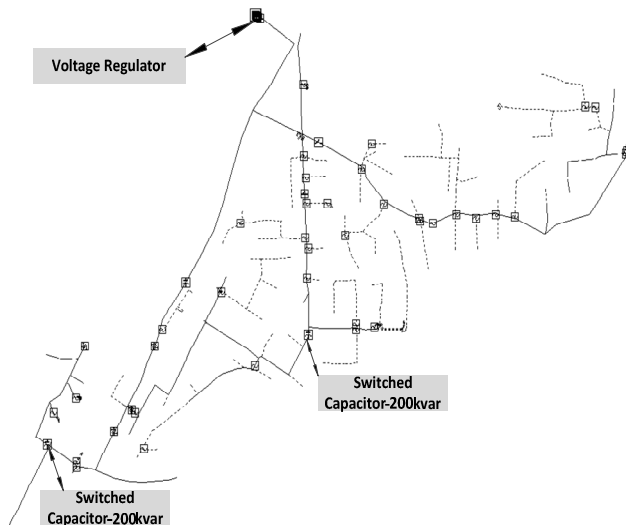


Figure 1 Feeder-1(F-1)

of the system due to faster convergence. The overhead and underground line of the distribution system was modeled in detailed using Modified Carson's Equation [6]. Underground cables were assumed to be Concentric Neutral Cable.

A power-flow study (load-flow study) is an analysis of the voltages, currents, and power flows in a power system under steady-state conditions. In such a study, we make an

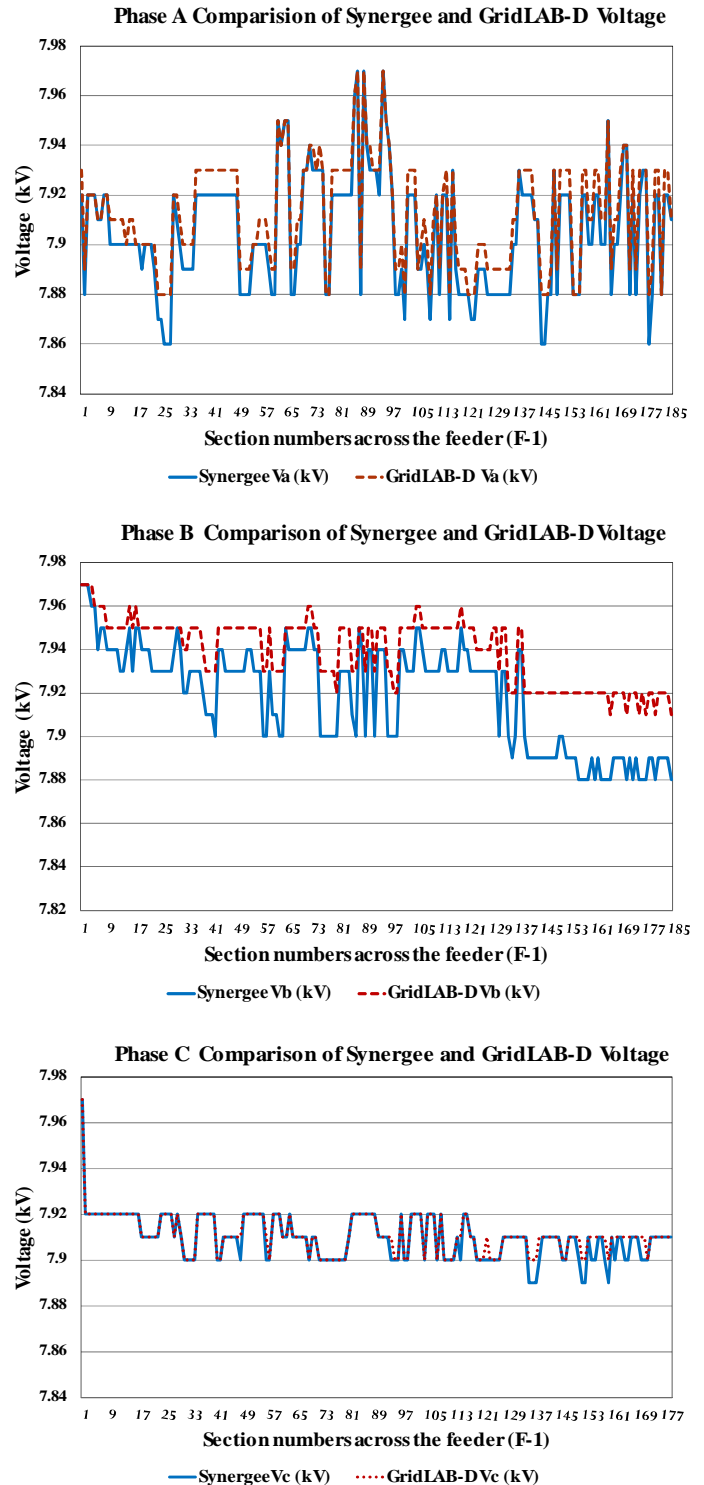


Figure 2 Voltage Comparisons

assumption about either a voltage at a bus or the power being supplied to the bus for each bus in the power system. Then determine magnitude and phase angles of the bus voltages, line currents, etc. that would result from the assumed combination of voltages and power flows. After the bus voltages are calculated at all busses in a power system, alerts can be set up if the voltage at any given bus exceeds, for instance, $\pm 5\%$ of the nominal value. This is important since the power needs to be supplied at a constant voltage level; therefore, such voltage variations may indicate problems. Power-flow studies are usually started from analysis of the power system in its normal operating conditions.

Figure 2 shows the load flow results between two power system modules at different sections along the feeder. Difference between the results on an average for Phase A, Phase B and Phase C is 1%, 2% and 1% respectively.

III. END-USER LOAD MODELING

Feeder F-1 was populated with number of houses and commercial building. Houses were populated based on PNNL study analysis on 24 prototypical feeders where they divided the houses depending on following 9 categories [7]:

Table 1: Load Classification

Load class	Description
Residential 1	Pre-1980<2000 sqft
Residential 2	Post-1980<2000 sqft
Residential 3	Pre-1980>2000 sqft
Residential 4	Post -1980>2000 sqft
Residential 5	Mobile Homes
Residential 6	Apartments
Commercial 1	>35kVA
Commercial 2	<35kVA
Industrial	All Industrial

The same concept was implemented on Pullman Feeder by visualizing the location of feeder on Google Earth and dividing the loads on each section into one of the above mentioned categories. For the given feeder F-1 after doing load classification we got 1620 residential houses and 150 commercial buildings. Moreover, a particular load classification does not significantly gives the correct behavior of the exact model but the aggregating the results of all individual houses should nearly approximate the behavior of real load consumption. Within each house all the loads except HVAC and Water-heater are considered as static loads while other two are considered as dynamic loads. Since the power demand is directly or indirectly dependent on voltage, time of day, temperature, and season of the year, we required a climate file for the given location. Climate file for the Pullman, WA was obtained from weather website for the same year as we were having the DMS and smart meter data so that our results are consistent [8].

A. Static Loads

Static loads are considered in this work as loads without thermal cycles. For a given load without thermal cycle, the

real power consumed is constant at a given voltage when ON, and there is no control loop that cycles the device on and off. Thus, total energy consumed is a function of the supply voltage and the time duration it is on. When the voltage to the loads is lowered, the amount of power consumed changes. These loads can be represented by a physical model that includes widely applied composite load model to maintain the constant impedance, constant current or constant power (e.g. ZIP model is one kind of physical model) [9].

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

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

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

where:

- P_i real power consumption of i^{th} load
- Q_i reactive power consumption of i^{th} load
- V_a actual terminal voltage
- V_n nominal voltage
- S_n apparent power consumption at nominal voltage
- $Z_{\%}$ Percent of load that is Constant Impaedance
- $I_{\%}$ Percent of load that is Constant Current
- $P_{\%}$ Percent of load that is Constant Power
- Z_{θ} phase angle of Constant Impaedance Component
- I_{θ} phase angle of Constant Current Component
- P_{θ} phase angle of Constant Power Component

From previous papers [10] on ZIP model, ZIP parameters come out to be 30% Z, 70% PQ for residential Customer, 50% Z, 50% PQ for commercial and 20% Z, 80% PQ for industrial. So for Pullman feeder F-1 we finally considered $Z_{\%}=0.3$, $PQ_{\%}=0.3$ and $I_{\%}=0.4$ as composite ZIP model.

B. Dynamic Loads

In this paper HVAC and Water –Heater are considered as dynamic loads since they are loads with thermal cycles which means there is a control loop which determines when the load is energized and for how long. If we reduced the voltage supplied to any HVAC or water heater, the amount of time will increase for the given load to achieve the output as same as the output before reducing the voltage. For simulation of feeder F-1, only residential and commercial loads are considered as dynamic loads since the given feeder is 75.19% residential, 4.57% commercial and 0.24% industrial. Equivalent Thermal Parameter (ETP) model proposed by Pacific Northwest National Laboratory was used to approximate the response of electrical demand of HVAC system as a function of input, temperature, humidity, voltage and thermostatic set points [7], [9], [11]. For water heater, insulation level, height of tank, volume of water, etc. and requires a time series input of hot water demand to determine the operational characteristics of the device [7]. Depending on the season and time of the day, schedules were assumed for heating and cooling set points.

IV. VOLT-VAR CONTROL AND OPTIMIZATION

Voltage optimization and Volt-Var control scheme is desired application for a utility in the modern distribution automation. Mainly there are two variables on which this application depends: one is voltage regulation and second is reactive power control. Reactive power compensation is achieved in this particular feeder F-1 through the operation of two switched capacitors in order to maintain the power factor at the substation near unity. Voltage optimization is achieved through the operation of substation voltage regulators in order to regulate the voltage depending minimum voltage at the end of line and the voltage drop along the feeder. Through this mechanism, a reduction in peak load is observed and as a result of this annual energy consumption is reduced. Voltage optimization for feeder F-1 is achieved by reducing the voltage at regulator from 123 V to 120V so that peak demand is reduced and maintaining power factor within preferred limit by Avista Utility. Power Factor is maintained by switching capacitor on/off based on reactive power along the feeder.

A. Voltage Regulator Control

Voltage control scheme is implemented here as direct end of line measurements [12]. This method is preferred for optimization because it chooses the lowest end of line voltage from the set of voltages for all the individual houses we modeled.

Moreover, we move one step further, since our end use customer loads changes frequently we need to run the power flow continuously and obtain the optimal set points for the desired objective of optimization. Analysis is done for one of the season in a year but similar analysis can be carried out for rest of the year. Figure 3 shows the Regulator Tap Settings behavior for given feeder F-1 with three different cases:

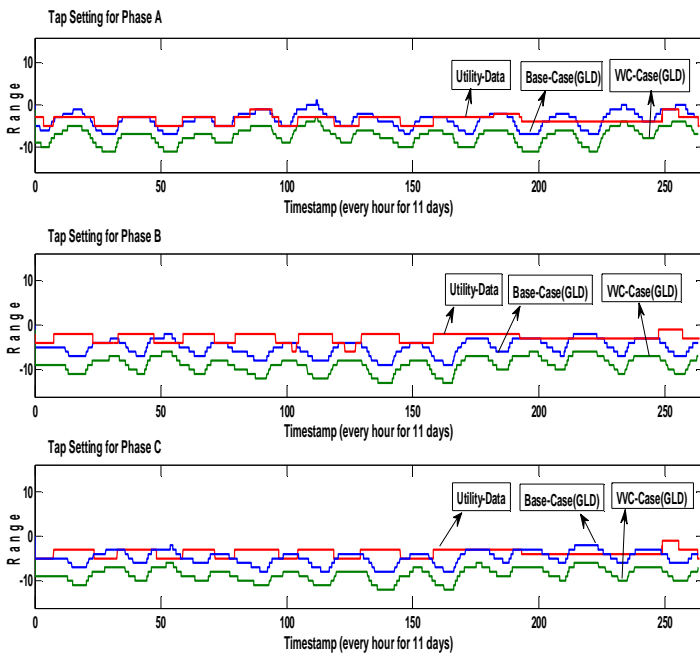


Figure 3 Regulator Tap Setting

Case 1: Data provided by the utility for 11 days

Case 2: Simulated Results in GridLAB-D with all individual houses populated with different loads (Base Case-GLD).

Case 3: Simulated Results in GridLAB-D with all individual houses populated with different loads and performing optimization (CVR Case/VVC-Case-GLD).

Case 1 and Case 2 are for comparison reason to check if the real time data provided by the utility and simulation results in GridLAB-D are in reasonable range after load modeling. Case 3 show the optimization results when we decrease the voltage to 120V base.

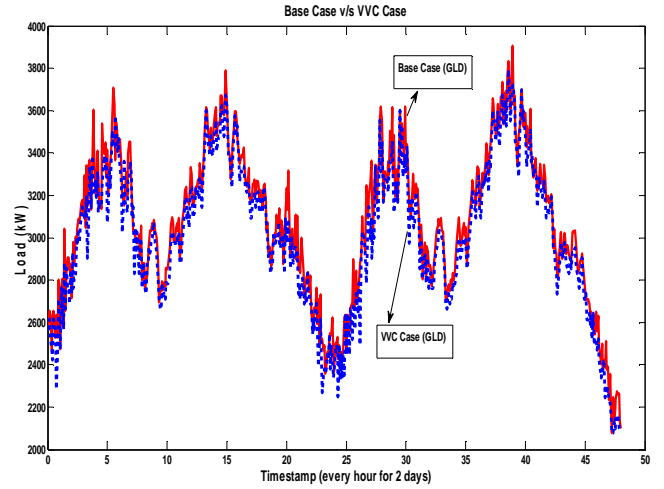


Figure 4 Comparison of Regulator Real Power between Base Case and VVC Case

Regulator real power, reactive power were calculated for Case 2 and Case 3 for every 5 minute interval. Figure 4 shows the regulator real power comparison for Case 2 and Case 3 for 2 days timeframe. Percentage energy savings for every 5 minute interval until 11 days was calculated based on both the cases and it came on an

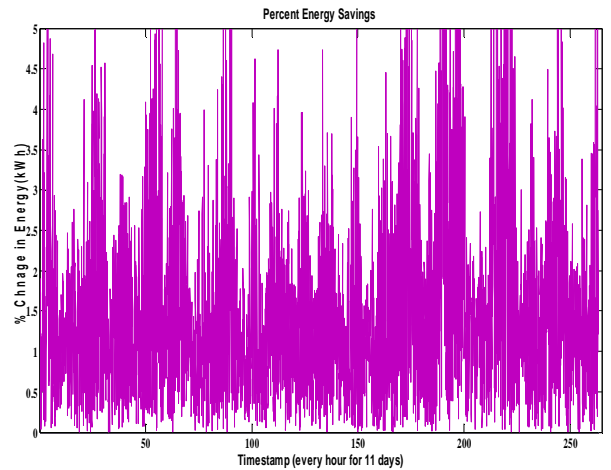


Figure 5 Percent change in Energy at Substation

average 3-4% as shown in figure 5.

B. Capacitor control

Capacitor is based on local power flow control scheme [12]. Capacitor controller uses local real and reactive power measurements for power factor control at the substation. The two switched capacitors shown in figure 1 are turned ON/OFF as per Avista Utility requirements:

- Turn ON switch capacitor if the power factor is below 0.95 lagging.
- Turn OFF switch capacitor if the power factor is below 0.98 leading

However, it was observed from the simulation results none of the switch capacitors were turned ON as power factor was found to be always above 0.98 lagging.

C. Voltage Regulation Analysis

a. Conservation Voltage Regulation at Substation:

CVR has been implemented based on one of the strategies name Line Drop Compensation (LDC). In LDC, a controller monitors the voltage at the feeder and raises or lowers the taps to maintain the specific EOL voltage. Change in the tap setting behavior at the substation regulator is shown in Figure 4. Considering two cases Case 2 and Case 3 as described before we try to calculate CVR factor given as follows:

$$\% \text{Change in Energy Consumption} = \left(\frac{kWh_{\text{base-case}} - kWh_{\text{VVC-case}}}{kWh_{\text{base-case}}} \right) * 100 \quad (4)$$

$$\% \text{Change in Voltage Reduction} = \left(\frac{\text{Voltage}_{\text{base-case}} - \text{Voltage}_{\text{VVC-case}}}{\text{Voltage}_{\text{base-case}}} \right) * 100 \quad (5)$$

$$CVR_f = \frac{\% \text{Change in Energy Consumption}}{\% \text{Change in Voltage Reduction}} \quad (6)$$

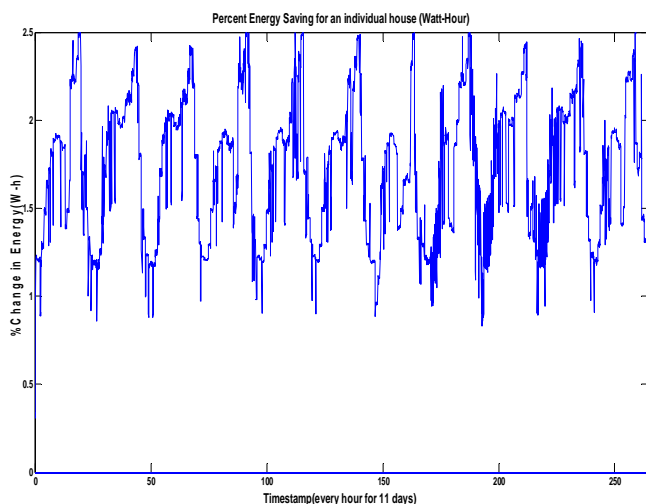


Figure 6 Percent change in Energy at individual house

CVR_f came out to be 0.72 for this specific feeder at substation.

b. Conservation Voltage Regulation at Individual Houses:

Since individual house model behavior are not 100 percent accurate we will take the average of Smart Meter Data for certain number of houses in that location and compare with simulation result of same number of houses and location of load model in GridLAB-D and the result is as shown below. And further CVR factor is also calculated at each individual house and then averaged at substation level. This was done to validate developed load model.

Energy change of an average 2% was observed at one of the house as shown in figure 6.

Finally this is a direct advantage to the utility who can decide how much reduction voltage they can do without losing the end user loads. With Volt-Var control scheme and optimization energy saving is observed with maintaining voltage at the customer end within operating limit (110V-126V) [2].

V. VALIDATION OF LOAD MODEL

Almost every house for given feeder (F-1) has Smart-Meter installed. Smart meter record data like Voltage, Energy used (Real Power and Apparent Power) and respective Smart-Meter number from each individual houses. This information is used as a feedback for achieving optimal set of control action at the substation.

Now to make our end user load model accurate and precise, we need to correlate that recorded data with the smart-meter data. The utility already provided the location (like addresses) information for each individual Smart Meter. We aggregated number of houses Real Power (kW) from the data provided by the utility on certain sections along the feeder. Similar procedure was performed for GridLAB-D simulated results.

Figure 7 shows aggregated results for one section along

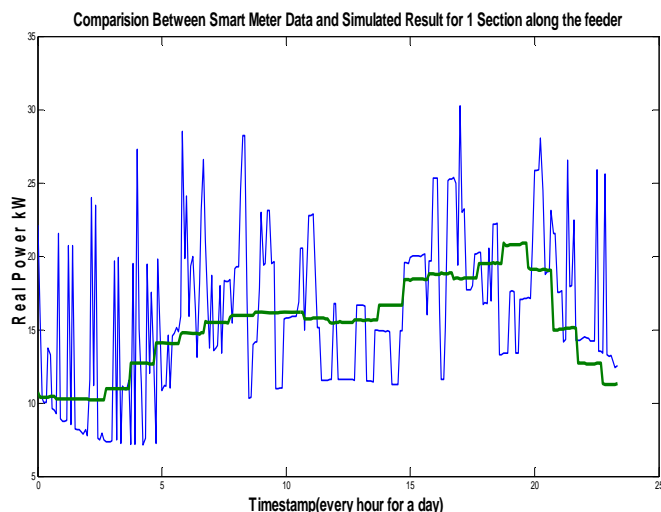


Figure: 7 Smart Meters and Simulated Result in GridLAB-D

the feeder. To clearly show the simulation result, only 1 day analysis is shown. Now to validate the load model we will use CVR factor as a comparison. We calculated CVR factor at substation and we calculated CVR factor at each individual houses. If we take an average of all the CVR factors for all individual houses it should come out to be equal to CVR factor at the substation. Average of all the individual houses CVR_f came out to be 0.725.

Now once we have validated CVR factor comparison, utility can easily determine the energy saving and peak load reduction as by equation (4). Moreover distribution transformer loss, underground line losses, overhead line losses was also determined but it does not have a significant impact when compared with VVC&O and without VVC&O scheme.

VI. CONCLUSION

Volt-Var control and optimization scheme were implemented with smart meter infrastructure on one of the distribution feeder in Pullman, WA. Simulation of load modeling was done in GridLAB-D, which is open source distribution tool. Load modeling was performed considering static and dynamic Loads. Simulation was done for 11 days for one of the season. Results show that 2-3% reduction in voltage gives an average of 3-4% of reduction in energy at the feeder. Annual simulation can be performed by extending same analysis. Further, losses occurring due to reactive power also decrease due to optimization. Once the end user load model for any of the feeder on distribution system is obtained, more smart grid features like demand response program, distributed generation coordination, electric vehicle integration can be added for energy saving and efficiency.

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