Analysis of Volt/Var Optimization in a Radial Distribution Network with DER Penetration

by

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The implementation of distributed energy resources (DERs) has provided the grid with many benefits. It has diversified the grid with new and advanced technology by adding energy generation to the electric power distribution sector. Although DERs make the grid more reliable and resilient, they can significantly alter the voltage profile and impact various voltage control devices. This causes the distribution system to experience unwanted losses, high maintenance costs, and reduced equipment lifetime. A solution to this is to implement an advanced distribution management system (ADMS). An ADMS is a software platform that manages grid assets, provides automated outage restoration, and optimizes the distribution grid's performance. This thesis investigates a function of an ADMS called volt/var optimization (VVO) within a specific distribution system. VVO utilizes volt/var control (VVC) devices and the conservation voltage reduction (CVR) technique in order to maintain an optimal voltage across the system. In this thesis, the IEEE 13 Bus system is employed for testing. The optimal Volt-Var setpoint is obtained using the Lagrangian to create a Python algorithm that provides an optimal solution given multiple constraints. Integrated with Python is the open-source distribution simulation software, OpenDSS. OpenDSS has the ability to simulate the system, provide analysis and alter VVC devices to maintain the calculated optimal voltage and vars induced throughout the 13-bus system. Being able to analyze and simulate this system will allow for a more efficient and modernized grid.

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1.0 Introduction

In the past several decades, technology has boomed at an exponential rate. Society has witnessed rotary phones turning into smart phones, old-style (CRT) television boxes turning into Smart TVs and basic watches turning into smart watches. It was only a matter of time to start changing the traditional power grid into a smart grid. In recent years, new devices and distributed energy resources were implemented in the power system. This was done to further modernize the grid; however, these new resources being added caused problems with efficiency in the distribution of power across the system. To combat this issue, advanced distribution management systems were added to the grid. These management systems provided the system with protection, reliability, resiliency and better efficiency [1]. This paper focuses on one of the modules of functionality for advanced distribution management systems. The specific functionality is referred to as volt-var optimization. In this study, volt-var optimization is explored to compute the optimal point of the system given various conditions and constraints. The methodology revolves around the use of OpenDSS. OpenDSS is an open-source software that has the ability to model distribution systems and run various simulations. Through the utilization of OpenDSS component object model (COM), Python is able to integrate with the software to implement an algorithm to achieve optimization.

1.1 Thesis Organization

Chapter 2.0 in this thesis covers volt-var optimization in the power system and the method to obtain it in this study. Section 2.1 focuses on providing background of two sectors in the power system, distribution and transmission sector. The second section of this chapter covers the five different modes of volt-var optimization. The optimization problem is then explored in Section 2.3 and briefly describes theories and equations to find a solution to the problem given various constraints.

Chapter 3.0 focuses on the measurements in the power system using phasor measurement units (PMUs) and other concepts revolving around them. Section 3.1 involves the understanding of instrument transformers related specifically to current and potential transformers. The first subsection gives an in-depth analysis of analog measurements. These analog measurements are then used to understand the process of analog to digital conversion. The following section introduces phasor measurement units and their functionality. The concepts from Section 3.1 are heavily involved in Section 3.2 to assist in understanding these PMU devices. Subsection 3.2.1 provides details on the contrast between PMUs and μPMUs.

The methodology to obtain optimization in the system is represented in Chapter 4.0. OpenDSS is explored in Section 4.1 to comprehend what is this open-source software and how it's able to model a distribution system. The following section presents information about the Python interface. The section includes details in integrating Python and OpenDSS to perform various simulations of a power system that are able to be controlled by an algorithm. Section 4.3 dives into the IEEE 13 Bus Feeder and its various components in the distribution system.

Chapter 5.0 displays the results of volt-var optimization in the IEEE13 Bus Feeder incorporated with DERs added into the system. The discussion of these results and the conclusion are presented in Chapter 6.0. Also, in this chapter, the future work is explained, as well as, how this thesis contributes to science on a theoretical basis. It also answers the question, “Where can I go next if given more time?”

2.0 Volt-Var Optimization

One of the main issues in the grid system is energy losses. A main contribution to these losses is ohmic, or I^2R. There are many methods to help solving this problem; however, a current method to reduce energy consumption is Volt-Var optimization (VVO). Volt-Var optimization uses volt-var control (VVC) devices in an optimal way by controlling the voltage and reducing the reactive power in the system. The voltage can be controlled two ways. The first is through changing taps on Load Tap Changers from the substation transformers and voltage regulators. The second method is utilizing the constant voltage reduction (CVR) technique [2]. In the distribution system, electrical loads are voltage dependent. This means when the terminal voltage is reduced, the customer at the last node load’s consumption is reduced as well. A problem that can occur from this is a voltage sag at the end of the feeder. Reducing the reactive power in the system can be done by installing shunt capacitors near the load center to decrease it from the substation.

2.1 Background of Distribution and Transmission Systems

This section will dive into more about the distribution and transmission systems. It highlights various components within the system and how they are applied within specific configurations. Basic concepts of each system are presented and related to the overall perception of this paper.

2.1.1 Distribution System

In today's power industry, distributions systems are significant of power delivery. These systems consist of various equipment such as transformers, feeders, switching and protection devices. The distribution system connects the transmission system to the customer and can be classified by three different configurations that are implemented in both distribution and transmission sectors. These are radial, ring/loop and inter-connected/network systems. The radial configuration implements one feeder or power source that delivers power to customers in one direction. In Figure 2-1, an example of a radial configuration is shown. Figure 2-2 shows the ring/loop configuration. This classification includes another source and switches that are placed in different locations. These locations are strategically set to continue power flow to customers. The system operates by supplying power from either direction until the power source fails or a fault occurs. At this moment, switches are in operation in order to reroute the power from the other source and countinuously deliver power to customers. The network or inter-connected configuration pictured in Figure 2-3 works similarly; however, there are additional power sources causing the system to increase in cost and reliability. Usually, distribution systems apply the radial configuration because of its simplicity and low cost to build. A main drawback is there's less reliability and in event of a fault, the entire line will lose power until the fault is cleared. Also, consumers who are further away from the feeding point experience a fluctuation in voltage [3]. Although the radial configuration is primarily used by the distribution system, the other two configurations are used in transmission systems.

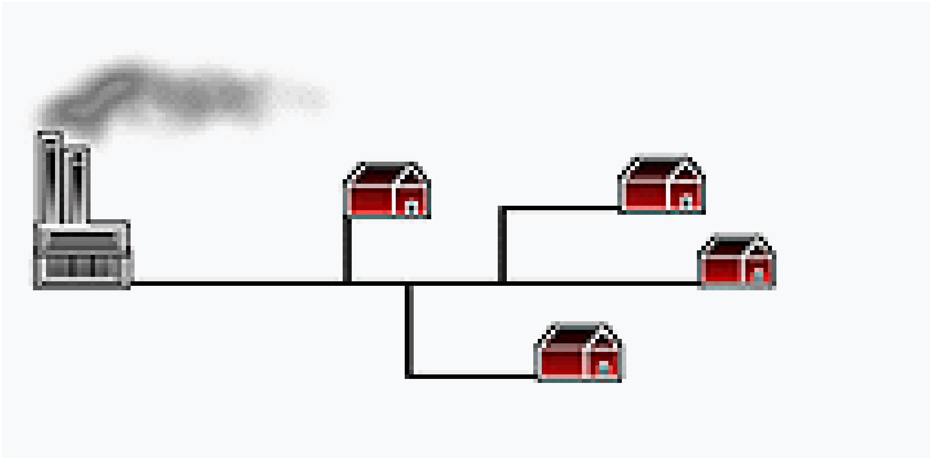

Figure 2-1: Radial Configuration [2]

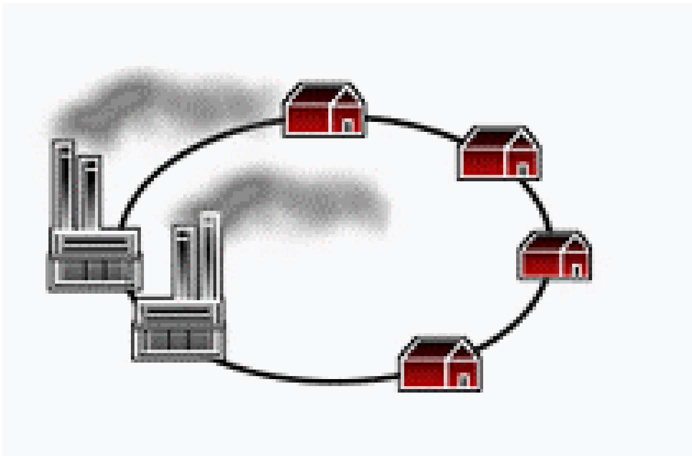

Figure 2-2: Loop/Ring Configuration [2]

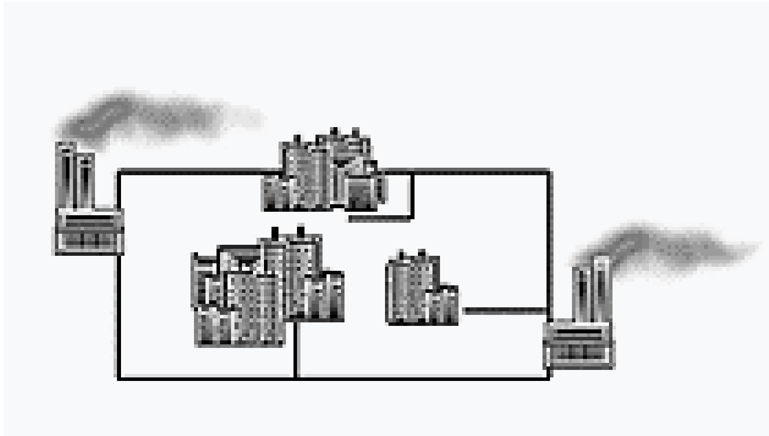

Figure 2-3: Inter-Connected/Network Configuration [2]

2.1.2 Transmission System

The transmission system includes transmission lines that deliver power. This is comparable to the distribution sector; however, the transmission sector carries high voltage at much longer distances. These longer distances between conductors causes the magnetic energy storage to be greater. In other terms, the inductance of the lines increases and leads to a higher X/R ratio than the distribution line. This is due to the material and cross section of the conductors being the same across both systems [4]. As a result, Var management is needed in order to minimize system losses and to support system voltage as well. Volt-var optimization is utilized to accomplish this in both the transmission and distribution sectors.

2.2 Modes of Volt-Var Optimization

There are five different modes of volt-var optimization. The first mode is referred to monitoring and control. In this mode, VVO does not run. This is due to advanced distribution management systems (ADMS) like SCADA still receive real-time supervisory control and data acquisition from the grid. The second mode is referred to loss optimization. VVO and all ADMS functionalities operate in this mode to improve the efficiency of the grid through managing reactive power flow [5]. Figure 4 shows these ADMS modules and their respective functionalities.

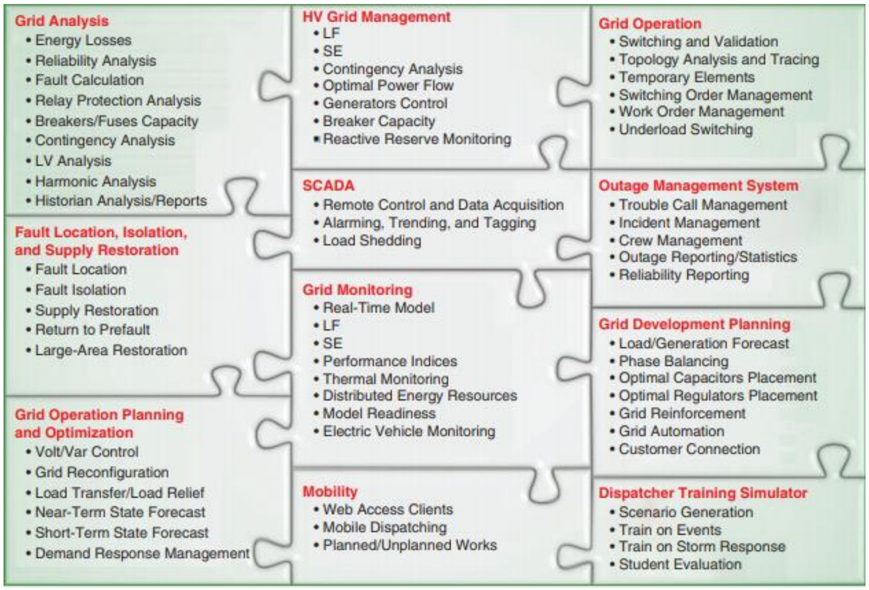

Figure 2-4: ADMS modules of functionality[5]

The third and fourth modes of volt-var optimization are called distribution system demand response (DSDR) and emergency, respectively. Both of these methods focus on reducing load on the grid. However, the DSDR method uses closed-loop VVO in order to execute planned and economic-driven peak load reduction. The DSDR mode was built around the concept of conservation voltage reduction. In order to reduce the peak load in this mode, the voltage is reduced by the optimization of voltage regulators and capacitor banks. The result of this reduction in voltage is about a 2V bandwidth on a 120V base. Figure 2-5 shows the effects of DSDR mode. The emergency mode is similar to the DSDR mode, except it implements nonoptimized voltage reduction in the grid. It is mainly used in response to unexpected bulk system events. There are two levels within this mode. The first level is used more frequently due to events such as a generation unit tripping being offline; moreover, the second level is only implemented under severe circumstances. This mode permits fast voltage reduction by using the functionality of voltage regulator control except without the specified time delay setting for the tap change initiation. In this mode, each regulator on the grid is commanded by the ADMS switching sequence list functionality within a certain time frame [5]. Figure 2-6 shows the effects of the emergency mode with both levels being applied.

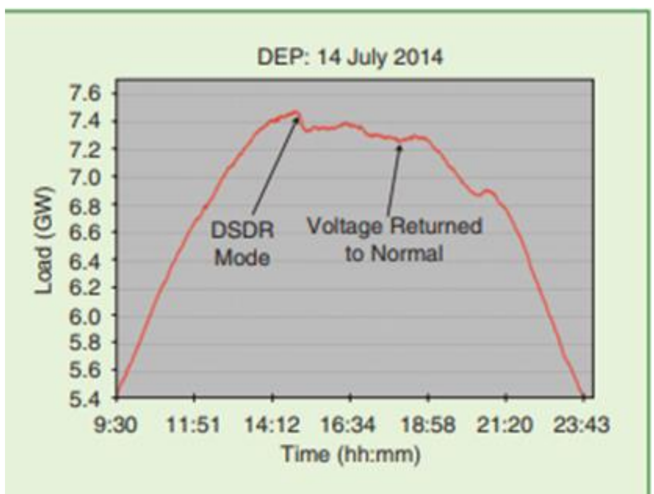

Figure 2-5: The effect of DSDR mode [5]

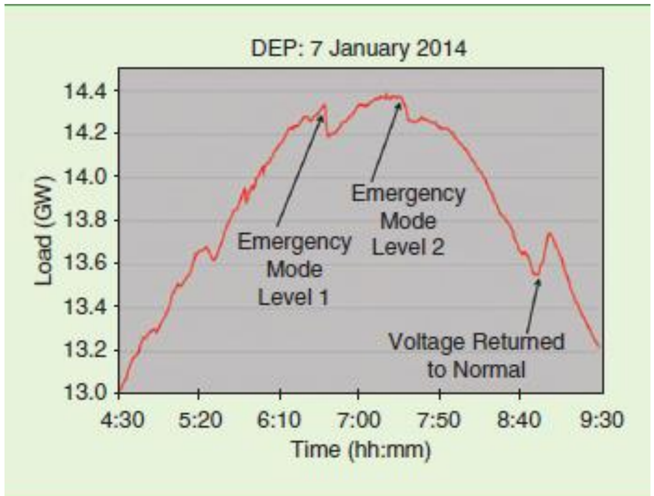

Figure 2-6: The effect of Emergency mode [5]

The last mode is referred to as Storm. In the Storm mode, a high degree of flux is within the grid due to a plethora of outages, am unknown device state or an incorrect topology. This mode is very similar to the monitor and control mode; however, it disables the use of VVO and all ADMS functionalities except for Load Flow (LF). This causes the voltage regulator control to return back to its default local automation settings and change the state of the grid from the previous ADMS mode. All the modes of VVO play significant roles in voltage control and load shaving.

2.3 Volt-Var Optimization Problem

In order to find the most economical solution to reduce voltage and load in the grid, optimization methods are needed. This section will be about the volt-var optimization problem and the mathematics behind it. The problem deals with the optimal scheduling of voltage and VAr compensation devices. These devices can be voltage regulators, capacitor banks and other CVR devices. The devices are dispatched in the distribution system and are subject to various constraints, such as, operating, distributive generations (DGs) and other environmental constraints.

A typical optimalization problem for volt-var control is a mixed integer non-linear type. A way to solve this is through the implementation of Primal-Dual Interior Point Method (PD-IPM). Conceptually, PD-IPM converts a constrained problem into an unconstrained problem with the use of adding slack variables, logarithmic function and Lagrangian multipliers. Afterwards, the unconstrained problem is solved using Karush-Kuhn-Tucker (KKT) first order necessary condition and Newton-Raphson method [6].

2.3.1 Lagrangian multiplier

The Lagrangian multiplier is a method implemented on minimization problems that have constraints. From the concepts of calculus, a maximum or minimum of a function occurs when the first derivative is equivalent to zero. In the same aspect, the gradient of the function that is being minimized, $\nabla f(\boldsymbol{x})$ is taken, in addition to the gradient of the constraints represented as $\nabla g(\boldsymbol{x})$. To take the gradient of a function is shown in equation (2.1). Also, to be noted, **x** is a vector made up of $\{x_1, x_2, \dots, x_n\}$ and **e**, $\{\mathbf{e_1}, \mathbf{e_2}, \dots\ \mathbf{e_n}\}$, is a vector of linear independent vectors that are within the subspace of $\mathbb{R}^n$ [7].

$$\nabla f(\boldsymbol{x}) = \frac{\partial f(\boldsymbol{x})}{\partial x_1}\boldsymbol{e_1} + \frac{\partial f(\boldsymbol{x})}{\partial x_2}\boldsymbol{e_2} + \cdots + \frac{\partial f(\boldsymbol{x})}{\partial x_n}\boldsymbol{e_n} \tag{2.1}$$

It is known that the gradient of the function that is being minimized, f, is normal to the constraint function, g. This means that the ∇f and ∇g are linearly independent of each other and can be ensured by using the Lagrange multiplier, λ, in equation (2.2).

$$\nabla f + \lambda \nabla g = 0 \tag{2.2}$$

The Lagrangian associated with (2.2) can be defined in (2.3) and the necessary conditions can be expressed in the form presented in (2.4) and (2.5) to find the optimal solution [8].

$$l(\boldsymbol{x}, \boldsymbol{\lambda}) = f(\boldsymbol{x}) + \lambda g(\boldsymbol{x}) \tag{2.3}$$

$$\nabla_{\boldsymbol{x}} l(\boldsymbol{x}, \lambda) = \boldsymbol{0} \tag{2.4}$$

$$\nabla_{\lambda} l(\boldsymbol{x}, \lambda) = \boldsymbol{0} \tag{2.5}$$

Figure 2-7 shows a graphical representation of the optimum solution when using Lagrange multipliers. It is noted that the objective and constraint functions both contain an extra variable, **y**, in order to see the optimal solution easier. Since both functions now have 2 variables, (2.3) can be rewritten as…

$$l(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{\lambda}) = f(\boldsymbol{x}, \boldsymbol{y}) + \lambda g(\boldsymbol{x}, \boldsymbol{y}) \tag{2.6}$$

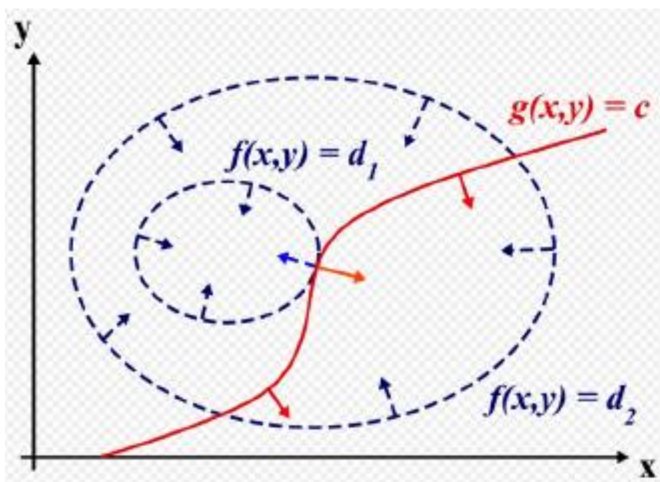

Figure 2-7: Graphical representation of using Lagrange multipliers to find an optimal soution [7]

The volt-var optimization problem consists of numerous constraints. The problem for an IEEE standard system is given by (2.7) [6].

min (Power loss + Consumer power demand) (2.7)

s.t:

Power flow equality constraints;	→ power system nature
Voltage magnitude inequality constraints;	→ IEEE standard
Bus voltage inequality constraints;	→system stability
Capacitor output inequality constraints;	→ practical meaning

The equality constraints are the power flow equations represented in (2.8) and (2.9) where Y_{ki} is the admittance matrix. Voltage magnitude constraints are given by ANSI C84.1 at a range of 0.95 and 1.05 pu [9]. The bus voltage and capacitor output inequalities are based on the system being implemented and its component's ratings [4].

$$P_k = \sum_{i=1}^{N} |Y_{ki} V_k V_i| \cos(\delta_i - \delta_k - \theta_{ki}) \tag{2.8}$$

$$Q_k = \sum_{i=1}^{N} |Y_{ki} V_k V_i| \sin(\delta_i - \delta_k - \theta_{ki}) \tag{2.9}$$

3.0 Measurements and Power Systems

Since the 1980s, the grid system implemented new technology has been evolving at a much faster rate. As a result, the grid became harder to monitor using the previous methods, for example, conventional SCADA. In order to maintain a secure operation of power systems, close monitoring of system operating conditions is required. Conventional SCADA is slow in time of operation for monitoring and control of the power system. It takes a few minutes to scan the system state and update causing failure to capture system dynamic events. If there's a stressed system condition or severe disturbance, proper control action can fail leading to the whole system collapsing. In the past, this was the main reason why blackouts occurred [10]. In order to combat this, phasor measurement units (PMUs) were implemented. These PMUs provide synchrophasor data that shows power system operators with real time events using indicators and parameters of the power system state. This chapter will discuss PMUs and concepts directly related to it such as, instrument transformers, phasors, analog measurements and A/D converter.

3.1 Instrument Transformers

In the power grid, voltage and current magnitudes are extremely large. This means that direct measurement is nearly impossible. In order to obtain these measurements, a transformer is used. A transformer "transforms" current and voltage by stepping the values up or down that is directly related to the turns ratio given in equation (3.1) and (3.2). When trying to measure the voltage and current in power systems, a specific type of transformer is implemented in the system called an instrument transformer. An instrument transformer steps down the level of voltage and current; however, there are two specific types of instrument transformers. These transformers are referred to as current transformer (CT) and potential transformer (PT) [10]. Figure 3-1 and Figure 3-2 shows a simple schematic of a CT and PT respectively.

$$\frac{I_p}{I_s} = \frac{N_s}{N_p} \tag{3.1}$$

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \tag{3.2}$$

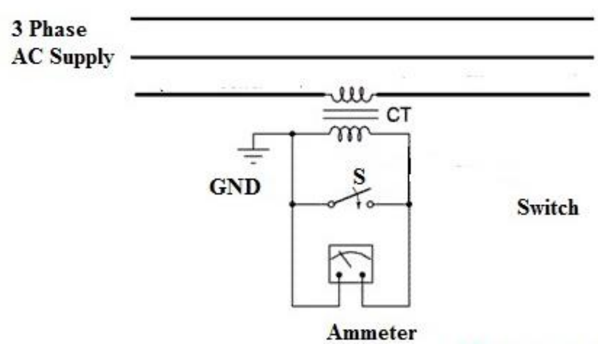

Figure 3-1: Simple schematic of a current transformer [10]

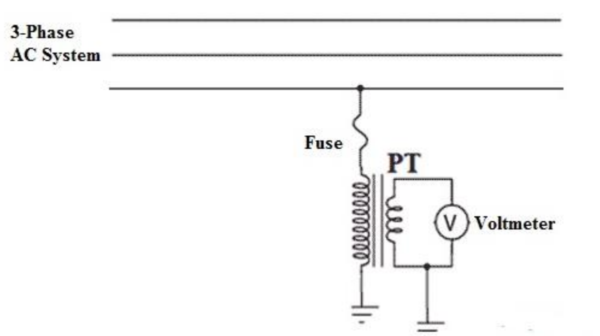

Figure 3-2: Simple schematic of a potential transformer [10]

A CT has primary windings that is connected in series to the power circuit. The secondary windings include a large number of turns to step down the current and is connected directly to an ammeter. It is usually rated for 5 amps and grounded to avoid shock. There's also a switch that is presented in Figure 3-1 that has a functionality of short circuiting the secondary terminal. This assists with avoiding high flux in the core that causes excessive core losses, leading the current in the secondary to be zero when the switch is left open. A PT uses the same basic principle as CTs except instead of stepping down the current, the voltage is being stepped down. This is done by having the primary windings with more turns than the secondary because of equation (3.2). Also, the voltmeter is connected in parallel to the secondary in order to measure the potential difference in the secondary coil [10]. Due to safety reasons, as for the CT, the PT has its secondary grounded. Although they are built differently, these instrument transformers are needed to take in analog signals in order to analyze various analog measurements.

3.1.1 Analog Measurements

The voltage and current through the distribution system are analog signals. These signals are normally sinusoidal waveforms with a specific magnitude, V_m, and phase angle depending on the source and the orientation of the system. (3.3) shows an equation of a typical sinusoidal waveform that is represented in the system. Each sinusoidal waveform can be represented as a phasor with a magnitude equivalent to the rms value of the waveform represented in (3.4) distributed on a real and imaginary axis. In an ideal case, it assumed that the signal is considered a pure signal consisting of a single frequency component and a constant phasor representation given in (3.5) [11]. Illustrated in Figure 3-3 is a sinusoidal waveform and its given phasor representation where the positive angles are measured counter-clockwise from the real axis. It is to be noted that signals in the power system are not pure in real time and contains harmonics; however, PMUs extract just the fundamental frequency to perform power systems analysis.

$$v(t) = V_m \cos(wt + \phi) \tag{3.3}$$

$$V_{rms} = \frac{V_m}{\sqrt{(2)}} \tag{3.4}$$

$$V = \frac{V_m}{\sqrt{(2)}} e^{j\phi} = \frac{V_m}{\sqrt{2}} (\cos(\phi) + jsin(\phi)) \tag{3.5}$$

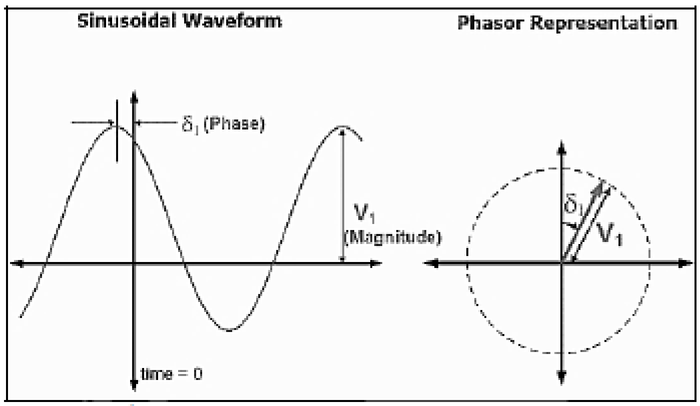

Figure 3-3 Signal waveform and phasor representation [11]

These analog signals are filtered through a passive low pass filter to block out the high frequency harmonics and maintain an approximate for the fundamental frequency. The result of the filter is fed to an analog to digital (A/D) converter.

3.1.2 Analog to Digital Conversion

An A/D converter is a device that takes an analog signal and transforms it into a digital or discrete form. There are 2 main steps in the process of transforming the signal. These steps are referred to as "sampling and holding" and "quantizing and encoding." The sampling and holding step utilize the Nyquist Theory, which states that the sample frequency must be at least double the signal frequency [12]. This is in order to prevent frequency signals outside the wanted signal band that are shown in the desired bandwidth, or in other words, aliasing. Following the Nyquist Theory, step determines the maximum bandwidth of the sampled signal. The sampling process is illustrated in Figure 3-4.

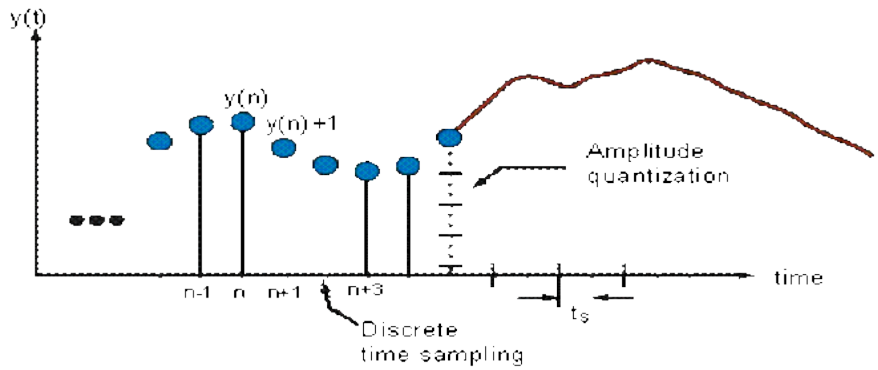

Figure 3-4: Sampling Process[12]

The quantization and encoding step partition the reference signal into discrete values and assigns the input signal to the precise value. The number of bits used to digitize the samples are referred to as resolution. The A/D converter has a finite resolution that results in a quantization error given in (3.6) since the input signal falls between quantization levels. The resolution depends on the number of bits in the discrete output and the reference voltage range. The equation is shown in (3.7). The equation shows ΔV, V_r, N, 2^N representing the resolution, reference voltage, number of bits in the output and the number of states respectively.

$$\text{Max Quantization Error} = \pm\frac{1}{2}\Delta V \tag{3.6}$$

$$\Delta V = \frac{V_r}{2^N} \tag{3.7}$$

$$\text{Digital Output Code} = \frac{\text{Analog Input}}{\text{Reference Input}}\,(2^N - 1) \tag{3.8}$$

Figure 3-5 displays the digital output code where the inputs to the resolution block are the analog and reference signals, resulting in the digital output represented in (3.8). The quantization process and transfer function the converter is illustrated in Figure 3-6 and Figure 3-7 respectively.

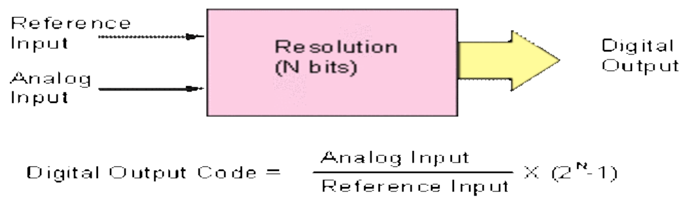

Figure 3-5: Discrete output code block representation [12]

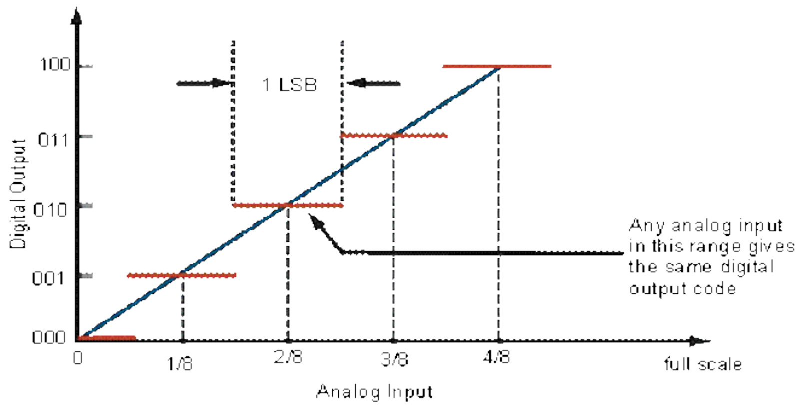

Figure 3-6: Quantizaiton process [12]

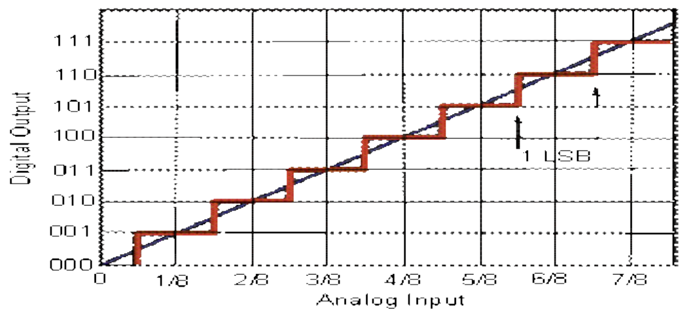

Figure 3-7: Ideal A/D converter's transfer function [12]

It is to be noted that the accuracy of the A/D conversion can be improved by increasing the resolution and sampling rate. This allows measuring the amplitude of the analog signal to be more accurate and also increases the maximum frequency that can be measured. Figure 3-8 represents a complete A/D system that is integrated in PMUs.

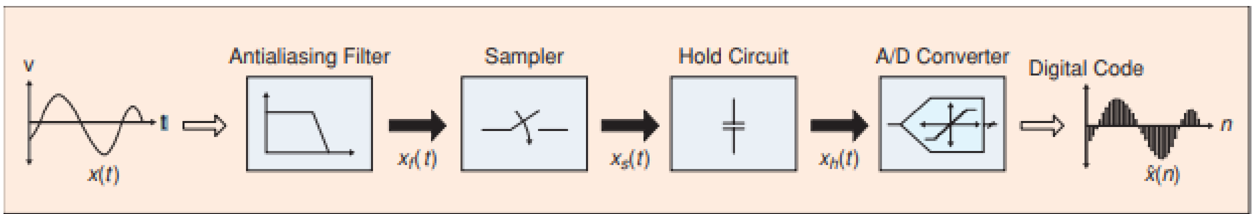

Figure 3-8: Complete system of analog to digital conversionon

3.2 Phasor Measurement Units

Phasor measurement units, or PMUs, have been around since the early 1980s and are deployed around the world due to various conflicts. These conflicts were particularly power outages in major power systems. IEEE stated that a PMU is "a device that produces synchronized phasor, frequency, and rate of change of frequency (ROCOF) estimates from voltage and/or current signals and a time synchronizing signal." [13]. PMUs provide accurate data that power system analysts use to calculate and analyze the sequence of events in the system that led to a blackout. Based off the results, exact causes and malfunctions can be obtained in real time. There are many different internal structures that PMUs come in; however, each one is similar from a conceptual standpoint. In Figure 3-9, the block diagram for a conventional PMU is shown.

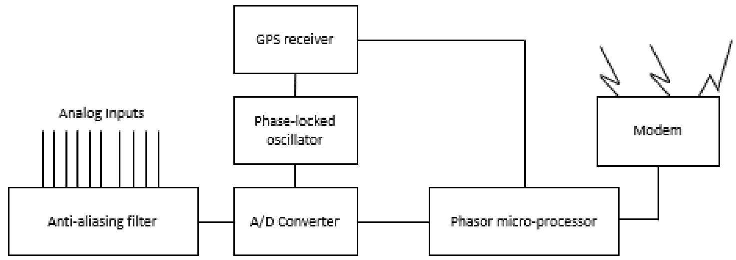

Figure 3-9: Block Diagram of Conventional PMU [11]

The block diagram shows the initial inputs are analog signals. These signals are the product of the current and voltage waveforms after being stepped down by an instrument transformer mentioned in the previous section. After filtering out unwanted high frequencies and harmonics in the anti-aliasing filter block, the signals are fed to the A/D converter. The A/D converter outputs a discrete sample to the phasor micro-processor and phase-locked oscillator blocks. The phase-locked oscillator and GPS receiver are used in conjunction to provide a common reference signal for synchronization. The main component of the phasor micro-processor are the digital signal processors (DSPs). These DSPs are used for phasor computations by utilizing the discrete Fourier transform (DFT) technique to determine phasor representation of the input signals. The phasor representation of a given signal that consists of N samples over a data window is given by (3.9) [14].

$$\mathrm{X} = \frac{\sqrt{2}}{N} \sum_{n=0}^{N-1} x(n) e^{-jn\left(\frac{2\pi}{N}\right)} \tag{3.9}$$

The output of the phasor micro-processor is delivered to the modem to communicate the phasor computations to various devices.

PMUs serve more purposes than just monitoring signals throughout the power system. They are also implemented to give solutions of complex protection problems and improve slow response times in protection functions. These protection problems can be anything from backup relay protection to maintaining voltage stability of networks. Another purpose for phasor measurement units is power system control through the use of time tagging phasor data so control is based on the system's current state slightly in the past [15]. Although PMUs are dispersed through the power system for various reasons, their primary objective is to improve the system's reliability and protection as the grid becomes more modernized.

3.2.1 Micro Phasor Measurement Units

PMUs are typically deployed in the transmission system. The distribution system still needed PMUs and all of the benefits it provides; however, there's cost issues to implement PMUs on a distribution level. As a result, μPMUs were introduced into the system. This specialized PMU was also needed due to the differences between the distribution and transmission system, outside of the obvious voltage disparity. The phase angle and voltage magnitude resolutions are significantly lower in the distribution system [16]. White noise and harmonics influence measurements more in the distribution system than the transmission. There's also a need for more measurement units in the distribution system because of the increasement of DERs and other generation sources in the sector.

μPMUs and PMUs both serve the same purpose but the inner architecture differs slightly. Microcontrollers are the primary part of μPMUs causing it to have more digital components than in PMUs. Also, there's not a GPS receiver present in the μPMU; rather, they have access to a central GPS server to retrieve information and maintain synchronization. Figure 3-10 shows a block diagram of a typical microcontroller in the µPMU.

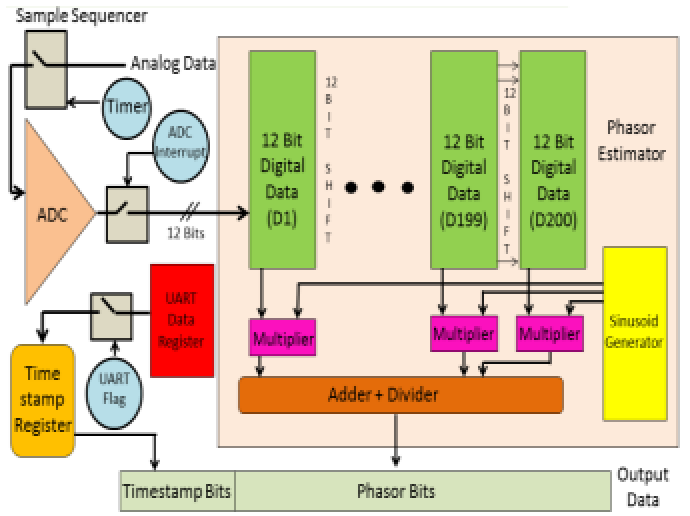

Figure 3-10: Block diagram of a microcontroller in a µPMU [15]

The microcontroller receives analog signals through certain allotted ports. The sampling frequency sets the sampling of the A/D converter and digitizes the signal while sending an interrupt when it successfully converges. Afterwards, the time data updates the reference time and then computes the discrete Fourier transform. The complex phasor is then stored and matched with a time stamp. The process of the microcontroller is represented by the flowchart in Figure 3-11.

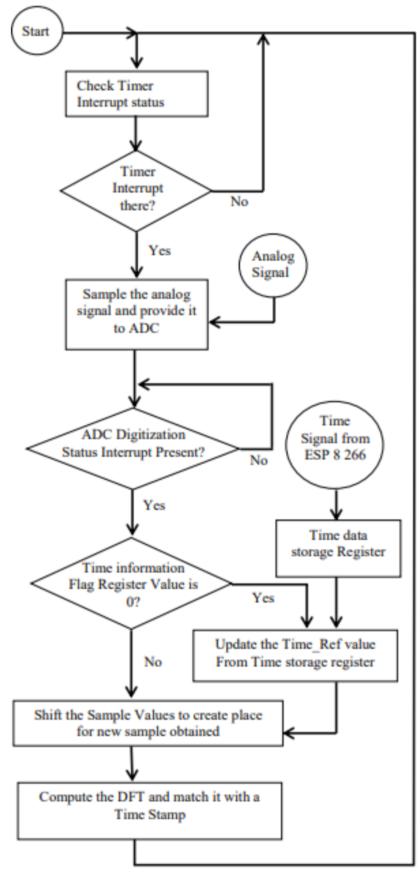

Figure 3-11: Process of the microcontroller in the µPMU

A study was done by the Bradley Department of Electrical & Computer Engineering at Virginia Polytechnic Institute and State University on the comparison of µPMUs and PMUs. The PSL µPMU model PQube3 and Arbiter PMU model 1133A are implemented for this research. The test composed of a Doble F2500 Single Phase Relay Tester as the 60Hz voltage source at 120V AC line-to-neutral with both models synchronized to a GPS using the same angular reference. Various events were created to compare the performances at a low distribution level. Three events from the tests to highlight are full voltage drop, phase angle change and frequency tracking [17]. Figures 3-12, 3-13 and 3-14 shows the graphical results of the three events respectively. To summarize, the µPMU was slightly slower and contained slight mishaps in the angle of the phase in the full voltage drop event. The PMU had some noticeable mishaps in the magnitude of the phase during the phase angle change event. There were also mishaps during the frequency tracking event.

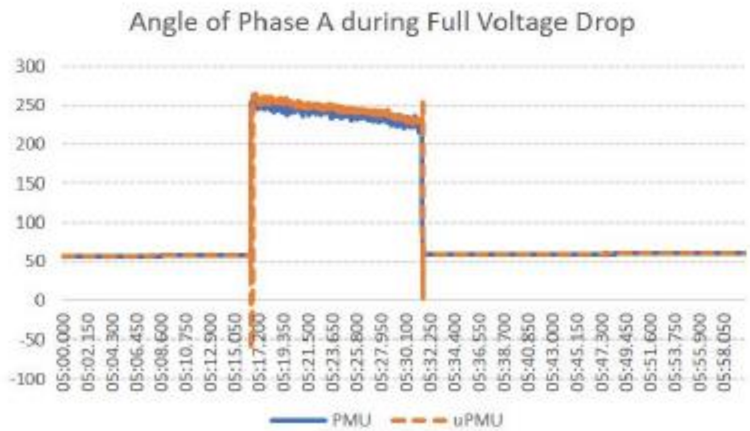

Figure 3-12: Comparison of PMU and µPMU in the event of a full voltage drop [16]

Figure 3-13: Comparison of PMU and µPMU in the event of a phase angle change [16]

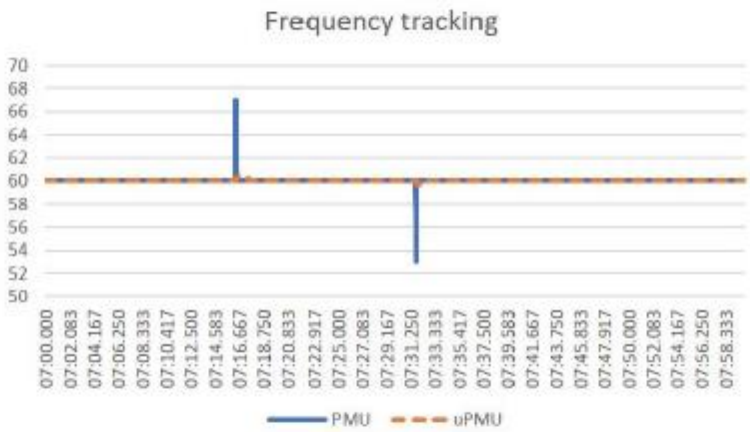

Figure 3-14: Comparison of PMU and μPMU in the event of frequency tracking [16]

4.0 Methodology for Optimization

This chapter introduces the use of OpenDSS and Python to compute the optimal values to achieve volt-var optimization in the power system. For this application, OpenDSS acts as a phasor measurement unit to measure phasor quantities within a distribution system. Integrated with OpenDSS to implement a volt-var optimization algorithm will be Python. The system being tested is the IEEE 13 Bus Feeder.

4.1 OpenDSS

OpenDSS is an open-source software created by EPRI that is widely used to perform planning and research of DERs (Distributed Energy Resources) since 1997 [18].The rapid pace of advanced DMS, distribution automation and DERs in the grid, created a need for a more robust system that could incorporate these new components in order to obtain grid modernization. Since OpenDSS is an open-source software that is designed to be indefinitely expandable. New modules can be added during any point and continue to run various simulations based on the components within the system. OpenDSS can provide many solution capabilities such as, unbalanced/multi-phase power flow, fault analysis, linear and non-linear analysis and much more. Using this software, VVO, line regulators and capacitor banks are able to be controlled. This is accomplished by also utilizing a system control interface (SCI). The SCI executes OpenDSS time-series simulations with ease by taking parameters and priorities written in the DMS script. Measurements from PMUs are needed for the SCI to take those values and implement within a specific algorithm [19]. Figure 4-1 shows the intercommunication of DMS scripts, SCI, OpenDSS and PMUs.

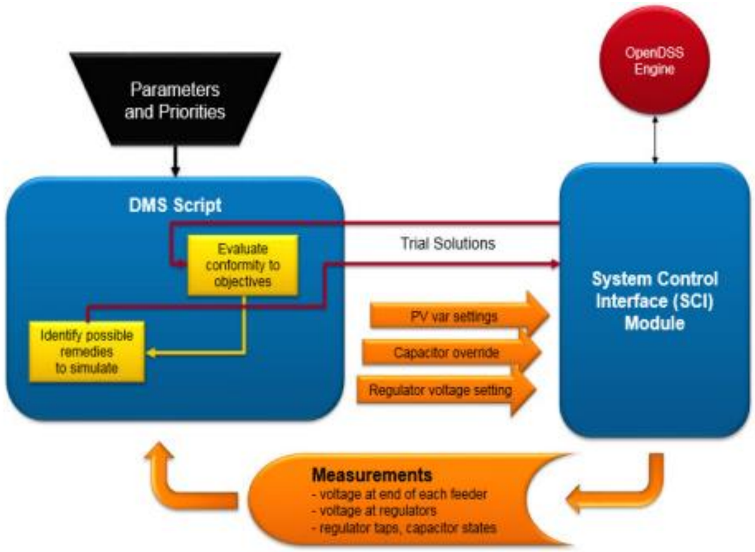

Figure 4-1: Intercommunication of DMS script, SCI, OpenDSS and PMUs [18]

4.2 Python Interface

OpenDSS has a component object model (COM) interface that can automate many simulation runs, extract results and perform required post-processing by allowing the user to manipulate the simulator programmatically. However, the COM interface is extensive and requires some unorthodox programming. As a result, many distribution planners use the SCI as a library or toolkit to simplify the process.

Python was used as the SCI for the application of this project. This is because Python is a free and easily downloadable software. Python also have many libraries that are freely available that can provide different analyses. The most important reason for using Python is the simple syntax and is widely known around the world amongst engineers.

The python package *win32com.client* assists the SCI module functionality by exploiting the OpenDSS COM interface. OpenDSS solution process involves 3 parts in every time step to perform DMS control for specific applications [18]. These 3 parts are:

1) A solution with controls is completed until convergence.
2) Clean up operations are done at the end of each time step, e.g. sampling monitors and updating charge of a storage element.
3) Time is incremented and the loop starts back over.

Figure 4-2 shows the process of OpenDSS solution using control. The yellow box shows the first part of the time step. The second part is represented at the bottom of the yellow box. The third part is shown on the left-hand side looping back to the beginning. The control section inside the yellow box is created using Python and are where the parameters of DMS and control algorithm are implemented. This is shown as the 2 red X's represented in Figure 4-2.

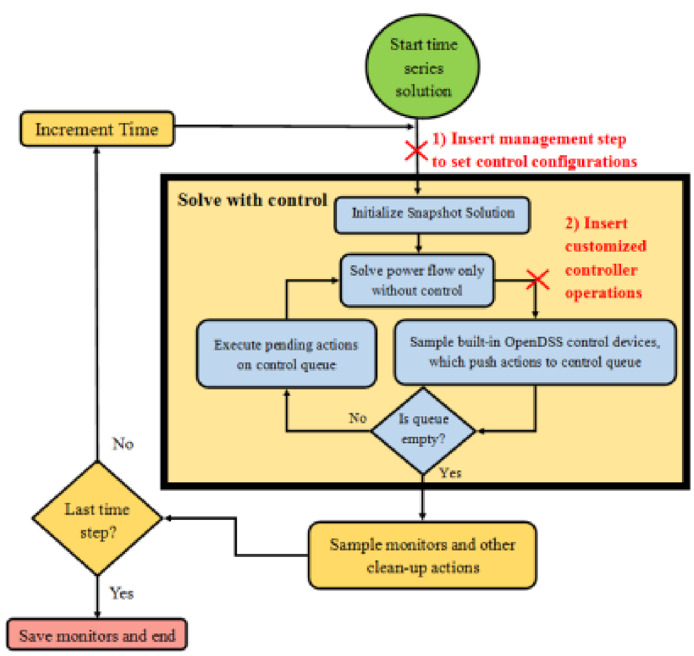

Figure 4-2: OpenDSS solution process [18]

4.3 IEEE 13 Bus Feeder

This project involves the use of Python and OpenDSS in order to provide volt-var optimization within a distribution system. The IEEE 13 Bus Feeder is the distribution system that is being tested with volt-var optimization for this paper. Figure 4-3 is a one-line diagram of the 13-bus feeder. The system consists of 10 lines that are overhead and underground and vary in phasing. Each of these lines are interconnected with the 13 busses, a generator, a voltage regulator, 2 transformers and 2 capacitor banks. The main transformer is a $\Delta - Y$ connected transformer that steps down the voltage from 115 kV to 4.6 kV. The in-line transformer is a $Y - Y$ connected transformer that steps the voltage down from 4.16 kV to 480 V. A couple of the busses are also connected to 2 types of loads. These loads are categorized as spot and distribution loads. A spot load is a load that is connected at a node whereas, a distribution load is a load that is uniformly distributed along a line section. For example, in Figure 4-3, a spot load can be identified at node **646** and a distribution load can be displayed between nodes **632** and **671**. Tables 1, 2 and 3 shows data and parameters for each load, line segment and capacitor in the system [20].

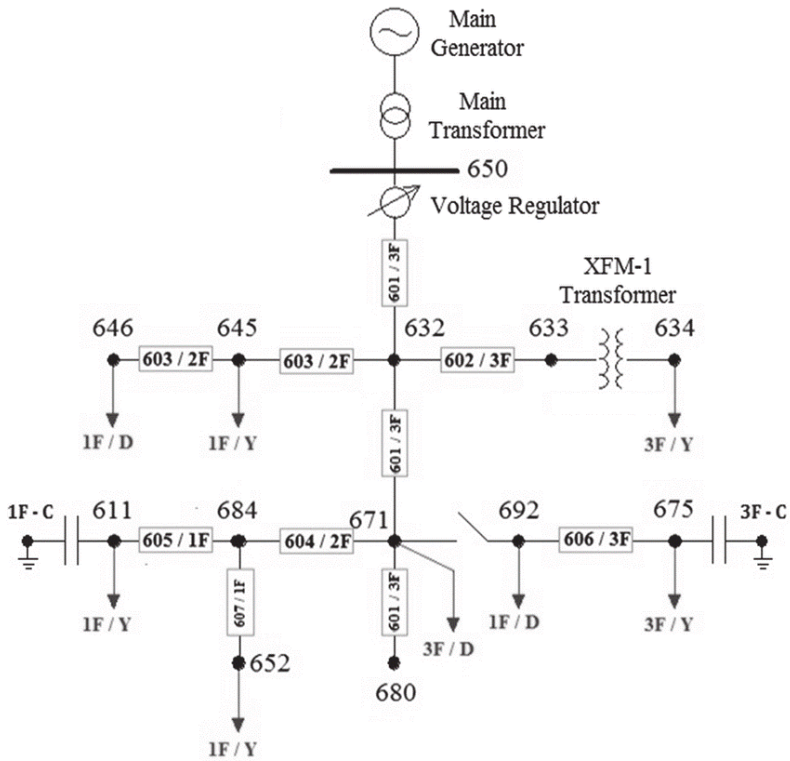

Figure 4-3: IEEE 13 Bus Feeder one line diagram [19]

Table 4-1: Spot and Distribution Load data

Node A	Node B	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
		Model	**kW**	**kVAr**	**kW**	**kVAr**	**kW**	**kVAr**
Spot Loads								
634		Y-PQ	160	110	120	90	120	90
645		Y-PQ	0	0	170	125	0	0
646		D-Z	0	0	230	132	0	0
652		Y-Z	128	86	0	0	0	0
671		D-PQ	385	220	385	220	385	220
675		Y-PQ	485	190	68	60	290	212
692		D-I	0	0	0	0	170	151
611		Y-I	0	0	0	0	170	80
Distribution Loads								
632	671	Y-PQ	17	10	66	38	117	68

Table 4-2: Line segment data

Node A	Node B	Length (ft.)	Config.
632	645	500	603
632	633	500	602
633	634	0	XFM-1
645	646	300	603
650	632	2000	601
684	652	800	607
632	671	2000	601
671	684	300	604
671	680	1000	601
671	692	0	Switch
684	611	300	605
692	675	500	606

Table 4-3: Shunt Capacitor data

Node	Ph-A	Ph-B	Ph-C
	kVAr	kVAr	kVAr
675	200	200	200
611			100
Total	200	200	300

5.0 Analysis and Results

The problem presented in Section 2.3 was carried out by utilizing the methodology represented in Chapter 4.0. The power flow of the IEEE 13 Bus system was simulated with varying cases. The objective was to analyze the system with and without DERs while implementing a volt-var optimization algorithm.

5.1 IEEE 13 Bus Simulation

The simulation was completed by modeling IEEE 13 Bus Feeder in OpenDSS and Python. In order to best analyze the impact of VVO on the system when DERs is added, a single bus between the added DERs is monitored. The bus is also connected to a spot load rated for 170kW and 125 kVAr. The bus being analyzed in the system is bus 645; moreover, the load is at node 645 which is also connected to the bus. A load shape was created for this load to further monitor the voltage throughout a 24-hour time window. The load shape shown in Figure 5-1 is a series of per unit values that represent how much of the load is being consumed during 24 hours. The graph of the voltage on the bus before and after implementing the VVO algorithm and any DERs is given in Figure 5-2. Since there were no DERs added, the optimization problem's solution closely matched the bus voltage before its implementation, resulting in the graph looking the very similar to the other.

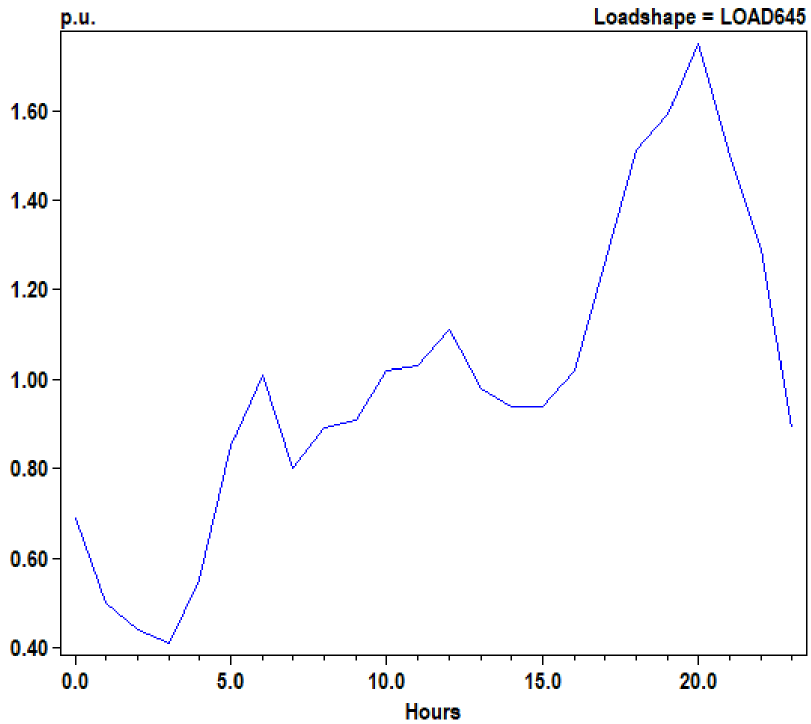

Figure 5-1: 24 hour load shape for Load 645

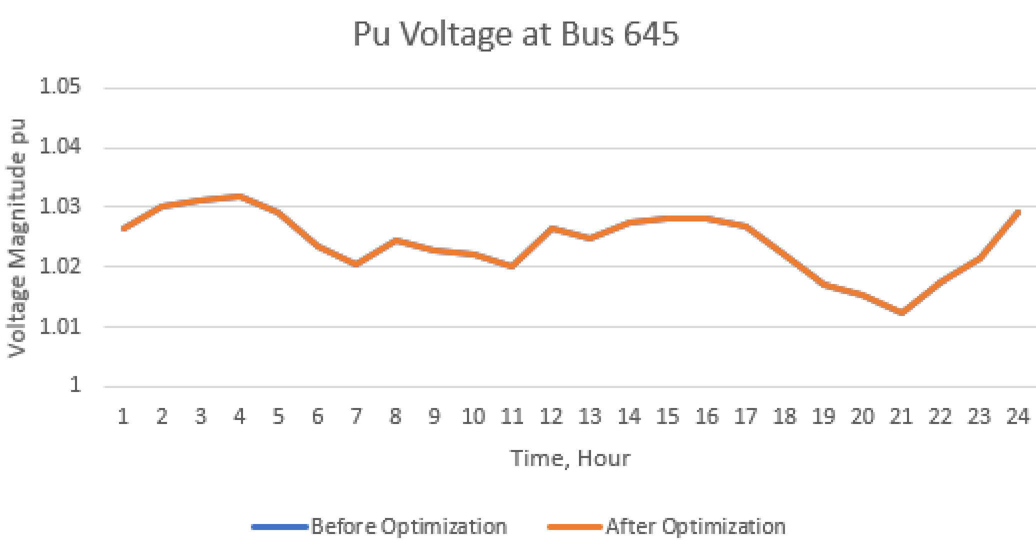

Figure 5-2: Per unit voltage at Bus 645 without DERs

When adding in DERs into the system, daily load shapes were created. Bus 632 received the PV system with a load shape given in Figure 5-3. The PV was placed at bus 632 to represent a precautionary measure. If the main generator fails, the PV is able to supply power to the grid for a small period of time. In order to maintain around the power delivered through the grid, the PV must be rated to handle close to the same amount of energy as the generator. For this case, the PV was rated at 5MVA. Accompanied with the PV in the system was a battery storage attached to bus 646. The load shape for the battery storage is shown in Figure 5-4. A typical storage capacity of a battery storage is around a one to a few hundred megawatt-hours. In this application, the battery storage is rated at 5 MWh. It is to be noted that in the graph of the load shape for battery storage, it shows that for short period of time in the beginning it is absorbing energy. Also, after about 17 hours, it starts to discharge and deliver power to the grid. Correspondingly, the PV delivers power to the grid until the battery begins to discharge.

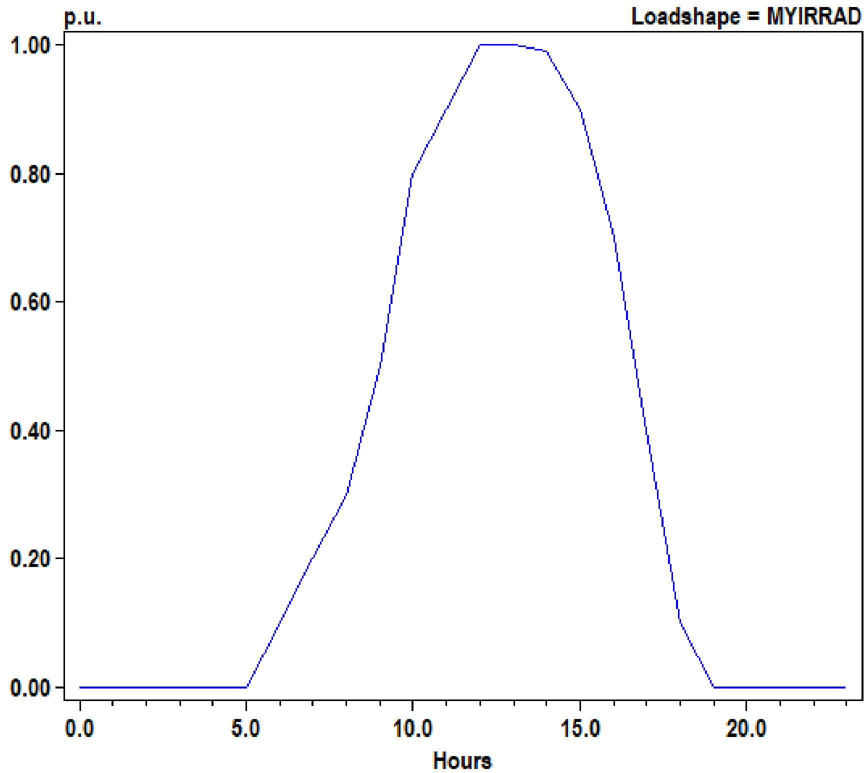

Figure 5-3: Load shape for PV in OpenDSS

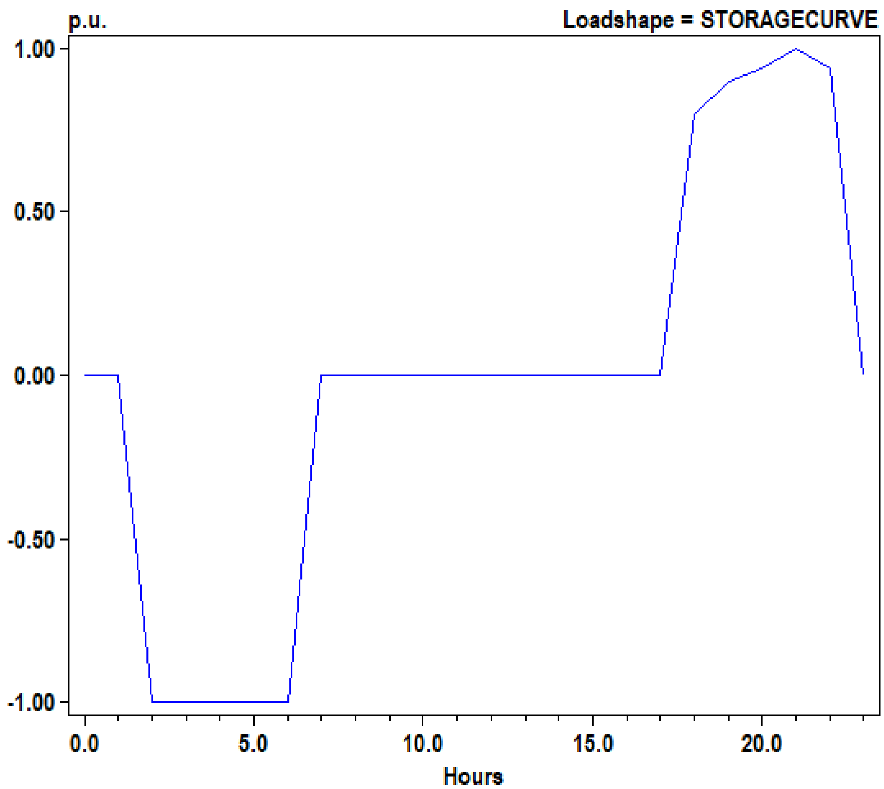

Figure 5-4: Load shape for Battery Storage

Figure 5-5 displays the before after bus voltage at Bus 645. Before the optimization algorithm was applied, the voltage at the bus violated ANSI standards and majority of the voltages were above 1.05 pu. When the algorithm was applied, the voltage dropped to below 1.05 pu; however, there's a huge dip at the time where the spot load is at its peak. The real power delivered at the bus was also tested, resulting in the same curve before and after the optimization algorithm was implemented. This is because the optimization problem that was used focused on changing the constraints of the capacitor banks to control the voltage in the system. As a result, the voltage decreased and the real power stayed the same causing the system to move toward a unity power factor. The graph of the real power delivered is represented in Figure 5-6.

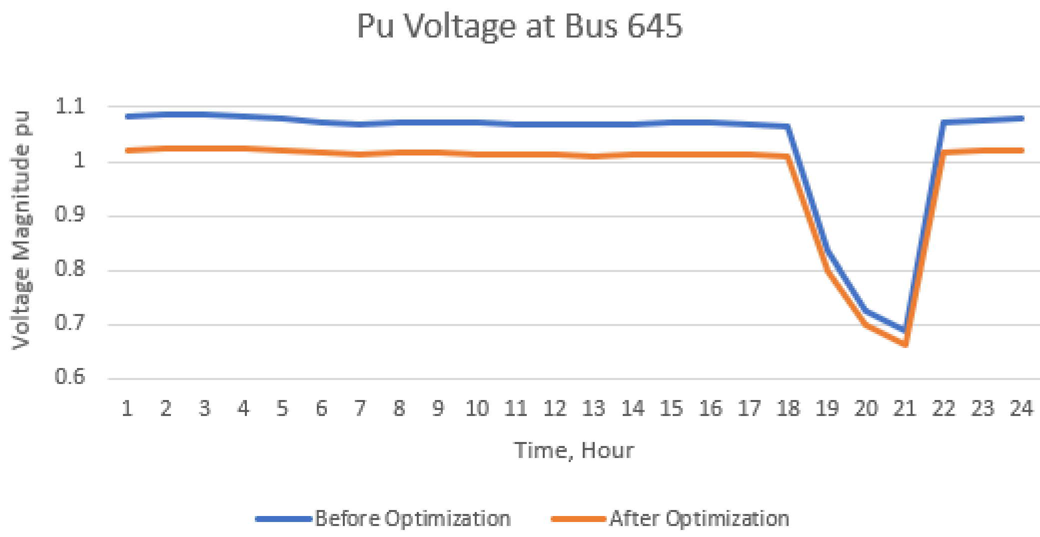

Figure 5-5: Per unit voltage at Bus 645

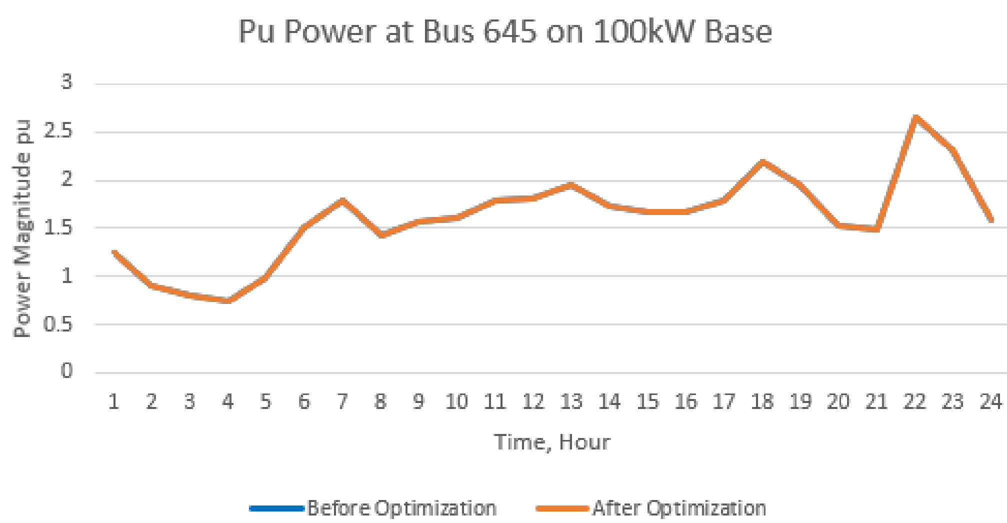

Figure 5-6: Per unit real power at Bus 645

6.0 Conclusion and Future Work

This work highlights the significance of ADMS module functions in the power system by exploring the use of volt-var optimization within the IEEE 13 Bus Feeder. After analyzing all of the graphs, conclusions can be made about the nature of the system. Controlling the amount of VArs being supplied into the system controls the amount of voltage and apparent power being distributed. With the implementation of OpenDSS, distribution systems are able to be modeled and simulated. As new devices are introduced into the system, these simulations will be key in creating a more efficient and modernized grid.

If given more time, the implementation of more and diverse DERs would be ideal. Analyzing the behavior of the system with these components could lead to a more reliable and resilient grid in not just America but in countries with very little access to power. Various ADMS modules can also be interrogated into the system to improve the efficiency of these grid. Using the knowledge gained from this research, a model can be created of University of Pittsburgh. Modeling the campus with different generators and power devices could move the campus towards an isolated microgrid. Other applications that could be done if given more time is analyzing many battery types, phasor measurements in state estimation and power flow studies in many conditions.

Analyzing different battery types would gain a further understanding of the impact each has on the power system. Even so, cost would play a significant role in adding a specific battery. State estimation is needed to analyze the power system in real-time. This is done by implementing the work in this paper to create an algorithm to estimate the state of the grid and report measurements to a control center. This follows into the idea of using volt-var optimization and calculating the voltage at different buses given a disaster, such as, a blackout or arc flash. A future study of these concepts would be beneficial and assist in improving the system today.

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