REDUCING ON-LOAD TAP-CHANGER OPERATIONS THROUGH UTILIZATION OF AUTO-SWITCH CAPACITOR BANK WITH PRESENCE OF LARGE SOLAR INTERCONNECTION

A Thesis by

Nicholus Cox

Bachelor of Science in Electrical Engineering, Wichita State University, Wichita, Kansas 2016

Submitted to the Department of Electrical Engineering and Computer Science
and the faculty of the Graduate School of
Wichita State University
in partial fulfillment of
the requirements for the degree of
Master of Science

December 2018

REDUCING ON-LOAD TAP-CHANGER OPERATIONS THROUGH UTILIZATION OF AUTO-SWITCH CAPACITOR BANK WITH PRESENCE OF LARGE SOLAR INTERCONNECTION

The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science, with a major in Electrical Engineering.

____
Visvakumar Aravinthan, Committee Chair

____
Chengzong Pang, Committee Member

____
Mehmet Yildirim, Committee Member

DEDICATION

To my Great Aunt Alice Criser

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Visvakumar Aravinthan for openly sharing his knowledge and guiding myself and other students through a path to success. After witnessing Dr. Ara's commitment to students, I enrolled in the Master's Program at Wichita State University and have not looked back. Many students including I owe their academic success to Dr. Ara. I would also like to thank my high school college advisor Courtney Bell for pushing me to persevere and attend a college of my choice. Ms. Bell continues to mentor me and many of her former students well beyond their high school career.

I would like to also extend my gratitude to my employers throughout college for offering opportunities for me to learn on the job and further my education at the same time. The flexibility of these employers allowed me to succeed academically and professionally. These employers are: McCurdy Auction LLC, Wichita High School South AVID, Wichita State University Career Development Center, Wichita State University Admissions Office, Wichita State University Housing and Residence Life, Dollar General, Integra Technologies LLC, Westar Energy Incorporated, Evergy Incoorporated, and C.H. Guernsey and Company.

Finally, I would like to thank multiple individuals for their commitment to my education and success throughout my life; my fiancé Caylin Wiley, my friends Nathan Lohkamp, Tsunkit Man, Kara Elder, and Whitney Roelfs, my mentors Connie Dietz, Ashley Cervantes & the McNair Scholars Program, Trish Gandu, Christine Schneikart-Lubbe and the Dean's Scholars Program, Brad Sweet, Dr. Sam Cohlmia and Sigma Alpha Epsilon Kansas Gamma Chapter, Dr. Victor Markovich and WSU Bands, Cara Ledy, Melonie Kiser, Samuel Zogg, Chief Graytok, First Sergeant Phillips and Wichita High School South faculty and staff, and lastly all professors and instructors at Wichita State University.

ABSTRACT

Voltage control is necessary on a power system to ensure all consumers are operating their equipment at a proper utilization voltage to avoid damage due to improper voltage supply. The traditional distribution power system is equipped with three primary assets to control voltage. These assets are load tap-changers (LTCs), which are sometimes referred to as on-load tap-changers (OLTCs), step voltage regulators, and capacitor stations. With newer technology these antiquated devices can become more intelligent and serve a more precise purpose with the addition of locally installed controllers. These controllers can be expensive but if used intelligently can pay for themselves over time by optimizing the devices they serve.

The addition of distributed generators (DGs) causes voltage control to become much more important. Rapid and dynamic changes in generation from solar, wind, diesel, and other forms of distributed generation can create voltage swings that are not tolerable in a traditional power system. Especially when these DGs have large megawatt generation capability. One downside of these voltage swings is the unnecessary tap changes the LTC or OLTC make to compensate for voltage deviations caused by momentary changes in power generation. The more tap changes an LTC make the less life the LTC has and replacement of an LTC can be one of the largest single unit expenses in a maintenance budget.

The research and analysis presented in this report demonstrate the negative impacts DGs have on distribution system voltage control and LTCs. Furthermore, a potential solution to reduce load tap changes is identified through intelligent control of capacitor stations. Analysis regarding placement of DGs and voltage control equipment are also reviewed and compared using IEEE 13 Bus System in OpenDSS. Finally, a cost-benefit analysis is presented utilizing equipment currently used in power systems throughout North America.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

Chapter Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

LIST OF ABBREVIATIONS

CSBI	Current Source Boost Inverter
CSI	Current Source Inverter
DBC	Dead Band Control
DER	Distributed Energy Resource
DG	Distributed Generator
DGA	Dissolved Gas Analysis
IEC	International Electrotechnical Commission
IEEE	Institute for Electrical and Electronic Engineers
LDC	Line Drop Compensation
LTC	Load Tap-Changer
MLDC	Multiple Line Drop Compensation
OLTC	On-Load Tap-Changer
OpenDSS	Open Distribution System Simulator
PCC	Point of Common Coupling
PT	Potential Transformer
SVR	Substation Voltage Regulator

CHAPTER 1

Introduction

The distribution power system is the fundamental tool used to deliver electrical power from a substation to an end user. This system can be large and complex in nature, not to mention fragile. A substation typically hosts a few key pieces of equipment for the distribution system. These devices are the substation transformer, circuit breakers and, voltage regulator or load tap-changer (LTC). The substation transformer converts the voltage from the transmission system to a more utilizable voltage on a distribution system. The circuit breakers are present to protect the substation transformer and other distribution equipment from eminent faults that could render these devices inoperable if exposed to a prolonged fault. Finally, the LTC is the device that regulates the voltage on the system to ensure all end users are receiving proper levels of voltage. LTCs can also take the form of step voltage regulators which can be located mid-circuit closer to a potential voltage problem.

1.1 Load Tap-Changer

The load tap-changer is the device in a transformer the automatically adjusts the voltage of the system based on the measured voltage on either the primary side or secondary side or both sides of the transformer. A potential transformer (PT) is often used to give the load tap changer controller a measurement of voltage to determine how much to adjust the voltage. The LTC adjusts the voltage by changing the turns ratio of the transformer through mechanical contacts. The contact will move to different ‘taps’ until the desired voltage is achieved. Typically, a voltage regulator is setup with a certain acceptable voltage bandwidth. Once the voltage exceeds the bandwidth a time delay begins, if the voltage remains out of band for the duration of the time delay the regulator changes taps in the correct direction to output nominal voltage. The regulator will continue to tap change until voltage is within the preset band[1].

Like most mechanical devices though, the LTC is known to fail which can cause abnormal voltage output and transformer failure. In fact, it is estimated that a third of all transformer failures can be related to LTC failure. Causes for LTC failures include, mechanical malfunction, increased contact resistance, thermal stress, breakdown of insulating oil, contact wear, and improper design [2]. Overuse of the LTC causes contact wear and so it is important to understand that the next tap change of an LTC could be the one that fails the unit. When introducing DGs into the power system a whole new level of difficulty is presented to voltage regulation.

1.2 Distributed Generation Voltage Impact

Recently, the concern of depleting fossil fuels and climate change have caused an increase in distributed generation (DG) implementations [3]. Distributed generation can take many forms but most commonly assumes the form of renewable generation such as rooftop solar, solar farms, single unit wind turbines, and fuel cells [4]. These new types of power generators could cause significant voltage instability and effect distribution systems more adversely than it would if interconnected with the transmission system. As the distribution system becomes more penetrated by DGs the voltage fluctuations increase and stability decreases [5]. This phenomenon can be witnessed in figure 1.

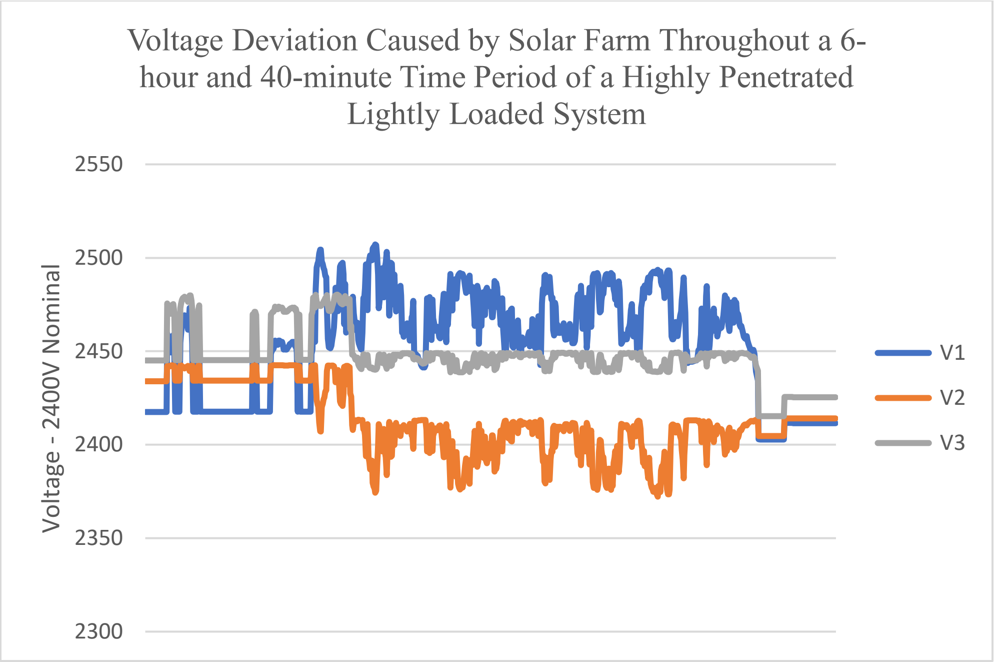

Figure 1. Voltage Deviation Caused by Solar Farm Throughout a 6-hour and 40-minute Time Period of a Highly Penetrated Lightly Loaded System

As previously mentioned, the primary units that maintain nominal voltage on a distribution system is the LTC and the step voltage regulators. When these devices function in tandem with a high penetration of DGs, LTCs and step voltage regulators could become overused by excessively tapping to mitigate voltage deviations caused by DGs. Overuse typically relates to shorter lifespans of LTCs and step voltage regulators. Which in turn end up becoming a financial burden and potential safety liability.

1.3 Problem Statement

Since utilization of DGs will continue to increase to reduce fossil fuel consumption and air pollution, the threat of increasing voltage instability only continues to grow. The increasing instability causes LTCs and step voltage regulators to be over used and thus decreases the life span of these units. This thesis will address the addition of solar farms on distribution systems and offer a cost-effective solution to mitigate voltage instability and increase the life span of

LTCs and step voltage regulators. One potential solution is using auto-switch capacitor stations to counter voltage fluctuations that could cause an LTC or step voltage regulator to measure voltages outside the tolerable ranges.

1.4 Organization of Thesis

This thesis has been divided into seven chapters. Chapter 1 presents an introduction to the distribution system and briefly discusses the problem created when additional DGs are added to a system. Chapter 2 reviews the literature previously written in this research area. The Third Chapter provides extensive modeling used to prove the potential solution of an auto-switch capacitor station. An analysis of all data collected is given in Chapter 4. Chapter 5 gives a summary of the models and analysis performed. A cost analysis can be found in the Sixth Chapter. Finally, a conclusion wraps up loose ends in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

2.1 Optimizing LTCs or Step Voltage Regulators

Traditionally, voltage regulation has been setup in various “zones” of regulation. These zones are established by cascading LTCs and step voltage regulators to output desired voltage downstream [6]. If one voltage regulation device is not sufficient, then another will be placed when voltage begins to become less desirable. To adapt to future changes to the power system though, different voltage regulation strategies need to be brainstormed, researched, and tested to optimize the life of an LTC. This approach is great when the load is predictable downstream of the regulator and minimal DG penetration is present.

There have been a few voltage regulation strategies proposed to minimize tap changes of an LTC or step voltage regulator. These strategies typically involve the regulator monitoring the reactive power (VArs/Q) of the circuit and increasing or decreasing the LTC time delay or bandwidth to allow more time for downstream auto-switch capacitor stations to turn on or off [1] [7]. An example of such a setting is demonstrated in figure 2 from [1]. However, when incorporating DGs it is always not as simple as developing a VAr bias approach due to DGs not necessarily injected VArs into the system.

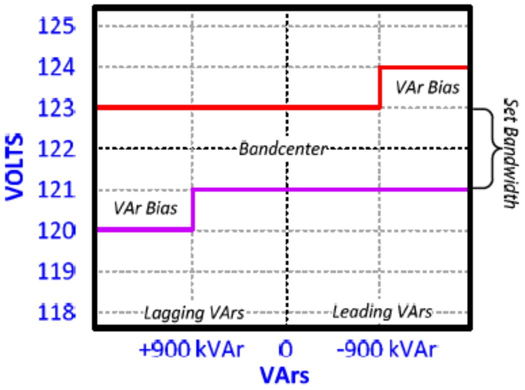

Figure 2 Band Edges Biased by VAR Flow from [1]

One other strategy for minimizing tap changes is the line drop compensation (LDC) method. To use this method a preset line impedance from the substation to the first customer is inputted to the LTC or step voltage regulator controller. The controller then calculates line voltage drop from that section of line and determines the proper tap position to supply the first customer with optimal voltage. This method is no different than conventual regulator control methods other than subtracting the voltage drop across the first section of line. A similar voltage control method that is use is known as multiple line drop compensation (MLDC) method. This method changes the tap frequency based on the historic load diversity on multiple circuits fed by the same substation LTC. MLDC will change the frequency of tap position changes by analyzing load diversity on all circuits rather than substation nodal voltage [8] Neither of these methods would be effective to mitigating additional LTC taps needed if high levels of DG penetration begin to occur due both methods only analyzing the load location and/or load profiles and not the DG characteristics.

However, a dead band control (DBC) algorithm could be proposed to be added to both LDC and MLDC. The DBC algorithm allows the regulator to skip tap changes when a transient load change occurs [8]. This could be a problem especially if the transient load swing is mis detected and consumers are then served inadequate voltage for an elongated period. The goal of a DBC control method is for the system to learn the difference between a transient and non-transient load swing. Unfortunately, DGs, especially solar generation, could operate at different output powers and shift generation without completely shutting off or maximizing output. So, the system would have difficulty learning without direct feedback from the DGs.

Minimization techniques have been used to optimize tap changes. These techniques typically look at worst case scenarios and/or only a couple load/generation combinations [9]

[10]. This is done by determining an objective function that will minimize tap changes while abiding by certain system constraints. Though the solutions that are found are in fact valid, it is necessary to understand that the power system is not a steady-state system and power system dynamics need to be considered.

2.2 Voltage Instability Caused by DGs

Voltage stability is crucial in a power system. Unstable voltage could lead to voltage collapse and cascading outages throughout a network. This impact along could take many man hours to correct and become burdensome on the power supplier. It has been noted that voltage deviations are prevalent in distribution systems with high penetration of PV [11]. These swings are significantly different than the standard voltage swings that occur due to system faults. When a system fault occurs on a low DG penetration circuit, the voltage regulation is already preconditioned to the nominal voltage output. But when a distribution system relies on power output by a DG or group of DGs the voltage regulation now is dependent on the present of the DG power output. If the contributions from the DG were to instantly disappear the system would need to readjust quickly be consumers experienced negative effects from the loss of voltage support from the DG.

One detail yet identified are the modes of operation for DGs. A photovoltaic generator can operate in two different modes, PV mode or PQ mode. The PV mode supplies the system with constant power and constant voltage. It is recommended to use PV mode when the circuit has a high penetration of DG units and /or the circuit is a weak source [12]. If the DG were to operate in PQ mode (constant power and constant reactive power) it is recommended to alter the angle of the voltage output such that the DG is injecting reactive power. This could be beneficial if one were to need additional voltage support on the circuit of the DG. The amount of reactive power injection needed can be difficult to determine due to the constant variance in a power system. There have been a few reactive power injection solutions recommended though.

2.3 Reactive Power Control Solutions for Voltage Support

One benefit of DGs is that they are most likely equipped with a current source inverters (CSI). These inverters allow engineers to determine the ideal current angle for the DG to generate at to supply the necessary amount of reactive power to the power system. Recent research and technology suggest that a current source boost inverter (CSBI) can be used to improve sustainable energy conversion in power systems [13]. One primary flaw in this technique is that power needs to be generating for any reactive power to be supplied to the system from a DG. So, the need for additional voltage support from capacitors will still be needed.

Minimization techniques can also be used for reactive power output. These objective functions target to minimize voltage fluctuations to reduce the voltage instability throughout the system [14]. Like CSBIs the minimization techniques for reactive power rely on the DGs to supply reactive power to the system. With DG integration the minimization technique injects more reactive power when needed to adjust for high demand periods. Similarly, the primary flaw with this technique occurs when DG penetration is not occurring. Resulting back to capacitor stations would still be necessary.

A final method proposed for reactive power control is a communication method between the substation LTC and switch bank capacitors downstream [15]. This method develops a two-way communication channel between the LTC and the capacitors such that the LTC would give commands to the capacitor to operate based on the system needs. This would be effective if communication is available in the area and cost was not a problem to establish a communication network.

CHAPTER 3

MODELING

3.1 Standard Model Used

The purpose of this work is to model how using an auto switch capacitor bank can reduce the number of tap changes experienced by a substation LTC when high penetration of solar photovoltaic generation is present downstream in the form of a single point of common coupling (PCC). This scenario often comes in the form of a solar farm. The standard model used to solve this problem is IEEE's 13 bus system in OpenDSS. The one-line diagram for IEEE 13 bus system can be seen in figure 3.

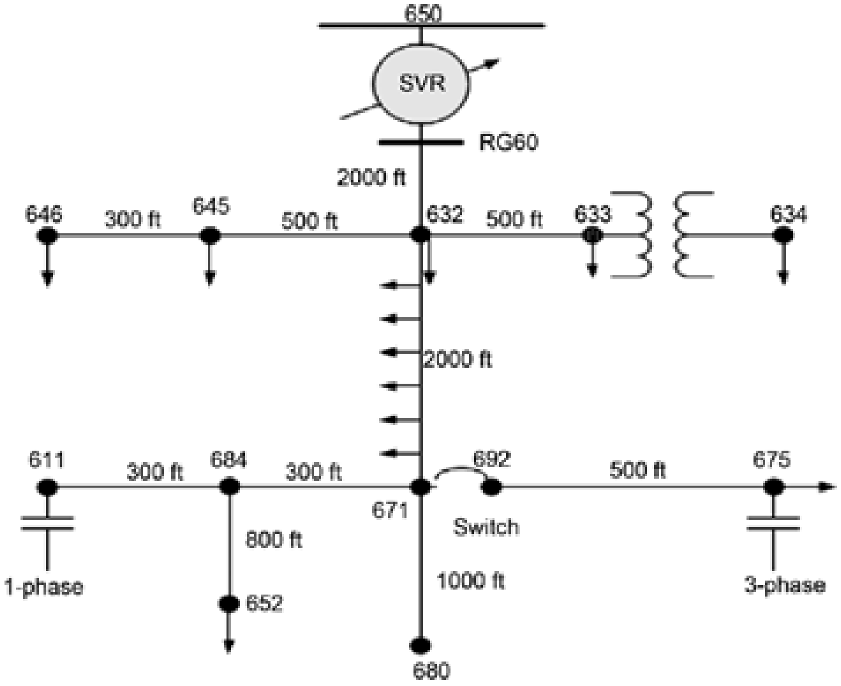

Figure 3 IEEE 13 Bus System

Two slight variations were added to IEEE's 13 bus system. One is that two additional load points were added at node RG60. These additional node points represent two different distribution circuits that share the same secondary bus of the substation voltage regulator (SVR). The blue boxes shown in figures 4 and 5 represent these additional circuits. The other variation is the addition of the PV system. In the “near source model”, the PV system is added to node RG60 as shown in figure 4. In the “far source model”, the PV system is located at node 680 as shown in figure 5. The PV system is indicated by the green octagon. Red triangles represent transformers or regulators and red squares represent capacitors.

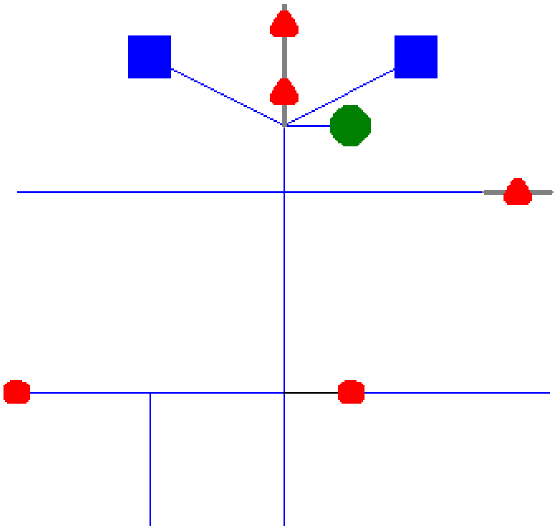

Figure 4 Near Source Model

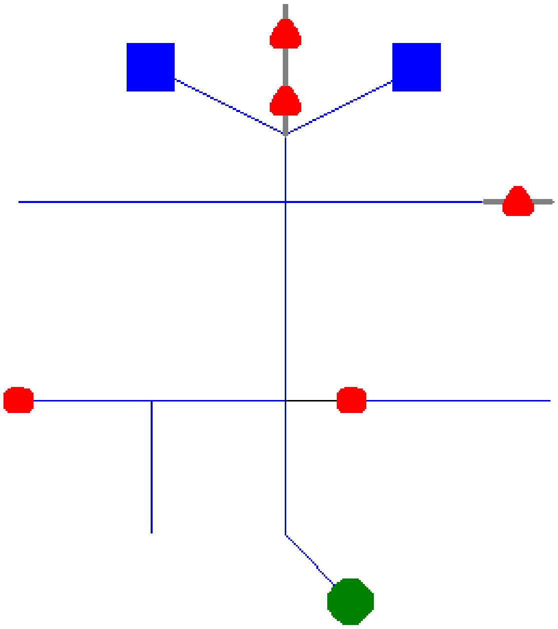

Figure 5 Far Source Model

3.1.1 General System Characteristics

The system modeled begins with a delta connected source bus. The source bus has a rated voltage of 115kV and is immediately connected to the high side of the substation transformer. The substation transformer has a wye connected secondary rated for a voltage of 4.16kV. Downstream of the substation transformer are the voltage regulators which will be discussed more in depth in a later section. The distribution circuit has an additional step-down transformer located at bus 633. That transformer has a high side rated voltage of 4.16kV and low side wye connection with a rated voltage of 480 volts. Two capacitor station are also located on the circuit which will be discussed more in depth in a later section.

3.1.2 System Loading

Two 48-hour per unit load curves were used to demonstrate dynamic loading characteristics of the circuit. These load curves can be seen in figure 6. Each nodal point designated with an arrow in figure 3 is a standard load location in the IEEE 13 bus system. Each of these load locations are assigned a maximum load depending on if the model is lightly loaded, moderately loaded, or heavily loaded. This assigned maximum load then corresponds with one of the load curves that is assigned to that load. The three loading scenarios for each load location and the load curve affiliated with that load location is outlined in Table 1. These loads and load curves were used in both the near source model and the far source model.

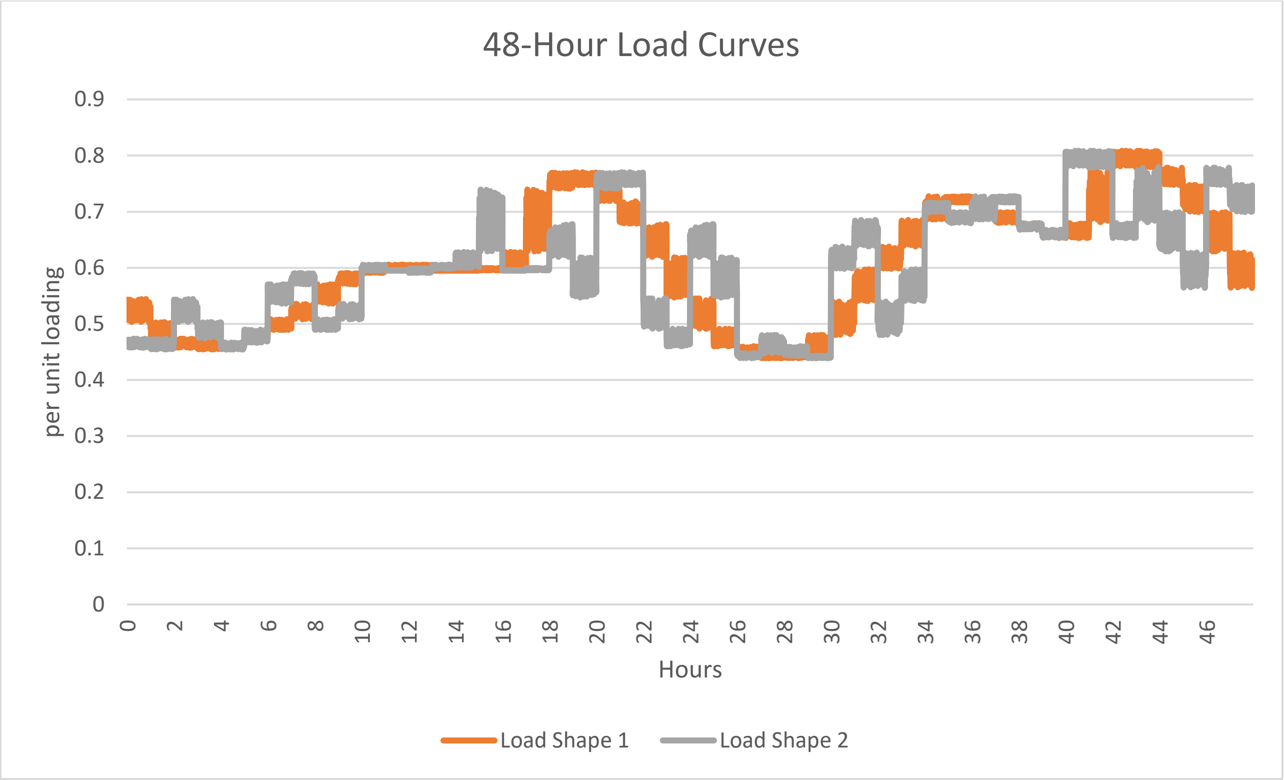

Figure 6 48-Hour Load Curves

Table 1 IEEE 13 Bus System Loading (kW)

IEEE 13 Bus System Loading in kW				
Node	**Lightly Loaded**	**Moderately Loaded**	**Heavily Loaded**	**Load Shape**
671	57.5	115	230	Shape 1
634 A Phase	80	160	320	Shape 2
634 B Phase	60	120	240	Shape 1
634 C Phase	60	120	240	Shape 2
645	85	170	340	Shape 1
646	115	230	460	Shape 2
692	9	18	36	Shape 1
675 A Phase	240	480	960	Shape 2
675 B Phase	34	68	136	Shape 1
675 C Phase	15	30	60	Shape 2
611	9	18	36	Shape 1
652	60	120	240	Shape 2
670 A Phase	95	190	380	Shape 1
670 B Phase	22	44	88	Shape 2
670 C Phase	59	118	236	Shape 1
RG60 Circuit 2	2000	4000	8000	Shape 1
RG60 Circuit 3	1000	2000	4000	Shape 2
Total	**4000.5**	**8001**	**16002**	

3.1.3 PV System Modeling

The PV system is modeled as a constant power constant voltage source. This mode for the DG was selected due to the research previously done in [12]. According to the researcher it is recommended to use constant power constant voltage mode when the circuit has a high penetration of DG units and /or the circuit is a weak source. The PV system was modeled with four different generation outputs depicted by Table 2. A per unit generation curve shown in figure 7 was used to correspond with the generation outputs. As purposely modeled day one represents a non-ideal generation day and the other represents an almost perfect generation day. This was done to witness how the model would react with both scenarios.

Table 2 PV Generation Outputs

Solar Farm Generation Outputs			
No Generation	**Light Generation**	**Moderate Generation**	**Maximum Generation**
0 kW	2500 kW	5000 kW	10000 kW

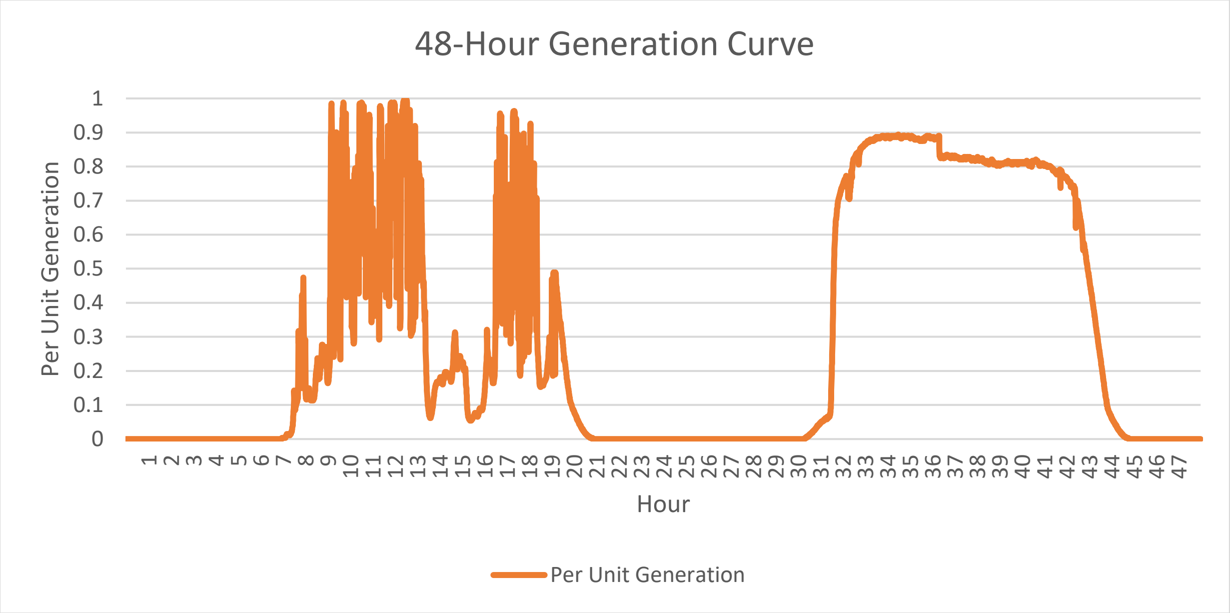

Figure 7 48-Hour Generation Curve

3.1.4 Substation Voltage Regulator and Capacitor Station Specifications

In this model there is one substation voltage regulator station serving the load of the three circuits. The regulator station is comprised of three voltage regulators (one per phase). The regulators each have a controller set to regulate at 120 volts on a 120-volt base. A bandwidth of 2 volts is given to each regulator meaning the regulator will operate within 118 and 122 volts. A time delay is given to the regulator of 45 seconds. The regulator is a standard 10% 16 tap regulator which means each tap will change the voltage 0.625%.

There are two capacitors in this model. The capacitor located at node 692 is a three-phase controlled capacitor station rated at 300kVAr (100kVAr per phase). The other capacitor is a fixed single-phase capacitor station rated for 100kVAr and located at node 611. This capacitor station is located on C phase. The controlled 300kVAr capacitor is set to close when the voltage goes below 1.0 per unit on any of the three phases at node 692 and remains on until the voltage exceeds 1.021 per unit. The final setting for the controlled capacitor is the addition of a 30 second time delay. The 30 second time delay is intentional to be less than the 45 second time delay of the voltage regulator.

3.1.5 Line Models

There are three line length models used as well to demonstrate how distance from the substation has a role in voltage stability when DGs are interconnected. The standard length is shown in figure 3. The other two line models double the line length and triple the line length. These three models will also be analyzed along with the load models and the generation models.

3.2 Formulation of Problem: Reduction of Tap Changes at Substation Voltage Regulator

As can be seen from figure 6 and figure 7 this model reviews 48 hours of load and generation data. The data gathered is a culmination of data points taken every 30 seconds for 48 hours. From the figures, dynamic characteristics can be seen for both the loads and the generation curves. To combat the dynamic nature of the solar farm, the switch bank capacitor was installed. It is anticipated that if the DG is operating and voltage at the DG is ideal, the capacitor will be off. If the DG were to spontaneously shut off due to cloud cover or any other condition, it is anticipated the capacitor will turn on to assist with voltage support. Without the switch bank capacitor, the system would rely on the substation regulator which is not ideal for the life span of the regulator. The goal of this modeling is to show that the addition of the switch bank capacitor will indeed decrease the number of tap position changes by the regulator.

3.3 Modeling Cases

For simplicity purposes the different cases are grouped into eight different groupings. Each grouping has 24 different cases for a total of 192 cases being analyzed. The eight groupings are as follows:

- Original Circuit Length – DG Far from Source
- Double Circuit Length – DG Far from Source
- Triple Circuit Length – DG Far from Source
- Original Circuit Length – DG Near Source
- Double Circuit Length – DG Near Source
- Triple Circuit Length – DG Near Source
- Original Circuit Length – DG Far from Source Adjusted BW on LTC from 2 to 4
- Original Circuit Length – DG Near Source Adjusted BW on LTC from 2 to 4

In each grouping all three circuit loadings will be analyzed with each of the four generation outputs. Along with these 12 cases a case will be added to analyze the impact of the switch bank capacitor to determine how many LTC tap changes were saved when the capacitor controller was enabled.

CHAPTER 4

ANALYSIS

4.1 Group 1: Original Circuit Length – DG Far from Source

The results for this group are shown in table 3. From table 3 it can be noted that the switch-bank capacitor saved 14 LTC operations throughout the 48 hours for the four different generation outputs and three different circuit loadings. The only scenario that brought a negative result with the scenario with heavy loading and 10MW of generation. The scenario created two additional tap changes when using the switch-bank capacitor. When reviewing the output file for this case it was found that the capacitor had initially turned off prior to generation even starting during the first 24 hour-period. The process of the capacitor turning off caused the additional tap changes recorded. If the capacitor was initialized to an off state, the number of tap changes would be identical with and without the capacitor for this case.

Table 3 Group 1 Results

	Original Circuit Length - DG Far from Source											
	Light Loading				**Medium Loading**				**Heavy Loading**			
PV Generation	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW
Taps without Capacitor	3	4	6	15	6	7	9	19	11	12	13	16
Taps with Capacitor	3	3	4	11	6	6	7	13	11	12	13	18
Capacitor Operations	1	2	2	4	1	1	1	2	0	0	2	6
									LTC operations saved in 48 hours:			**14**

4.2 Group 2: Double Circuit Length – DG Far from Source

The results for group 2 are shown in table 4. This group presented the first two unstable conditions in the power system when interconnected with the solar farm. Both unstable conditions occurred when generation was at its max and the capacitor switch was not functioning. One very important observation is that when the auto-switch capacitor is available the unstable conditions become stable. The instability in the group is due to drastic voltage swings upstream of the solar farm. The voltage instability experienced is shown in figure 8 below. To develop this chart, the line lengths were gradually reduced until the model could find a solution. Another positive impact of the capacitor in group 2 is that 9 LTC operations were saved in the cases that were stable.

Table 4 Group 2 Results

	Double Circuit Length - DG Far from Source											
	Light Loading				Medium Loading				Heavy Loading			
PV Generation	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW
Taps without Capacitor	4	4	4	12	5	5	8	Unstable	9	10	10	Unstable
Taps with Capacitor	3	3	4	11	5	4	9	9	9	7	7	10
Capacitor Operations	1	2	2	2	1	1	13	11	2	4	6	8

LTC operations saved in 48 hours: 9

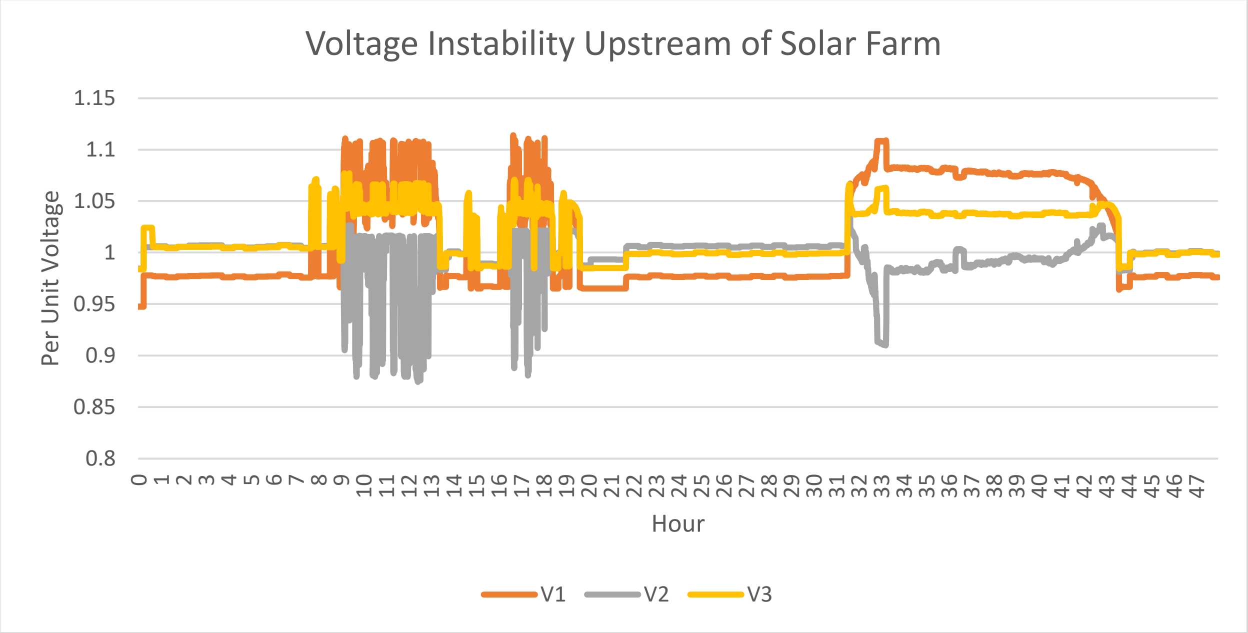

Figure 8 Voltage Instability Upstream of Solar Farm

4.3 Group 3: Quadruple Circuit Length – DG Far from Source

The results for this group are shown in table 5. Similarly, to group 2, group 3 saw unstable conditions arise due to voltage instability. These unstable conditions occurred both with and without the auto switch on the capacitor. When gradually reducing the line segments until a stable condition occurred an identical voltage profile to figure 8 was presented. It appears when a large DG is placed a great distance from the substation, unstable conditions become more prevalent. Other than the instability, Group 3 experienced a reduction of 10 LTC operations in the cases that were stable still proving that if the circuit is stable, the capacitor can be a benefit to the system.

Table 5 Group 3 Results

	Quadruple Circuit Length - DG Far from Source											
	Light Loading				**Medium Loading**				**Heavy Loading**			
PV Generation	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW
Taps without Capacitor	5	4	5	16	6	6	Unstable	Unstable	9	12	Unstable	Unstable
Taps with Capacitor	3	3	1	15	6	4	Unstable	Unstable	9	12	Unstable	Unstable
Capacitor Operations	1	2	4	1	0	9	Unstable	Unstable	0	1	Unstable	Unstable

LTC operations saved in 48 hours: 10

4.4 Group 4: Original Circuit Length – DG Near Source

The results for this group are shown in table 6. This is the first group of cases where the solar farm is located near the source. This group does experience more LTC tap changes than its counterpart in group 1. This is presumably due to the reliance on the LTC for voltage regulation since the solar farm is much closer in proximity. The capacitor also does not switch nearly as often as it does in group 1. There were 2 LTC tap changes saved though due to the auto-switch capacitor.

Table 6 Group 4 Results

	Original Circuit Length - DG Near Source											
	Light Loading				**Medium Loading**				**Heavy Loading**			
PV Generation	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW
Taps without Capacitor	3	4	11	60	7	7	16	57	11	13	20	63
Taps with Capacitor	3	4	11	60	7	7	15	57	11	12	20	63
Capacitor Operations	0	0	0	0	0	0	1	0	0	1	1	1

LTC operations saved in 48 hours: 2

4.5 Group 5: Double Circuit Length – DG Near Source

The results for this group are shown in table 7. An increase in tap changes can be seen in group 5. When compared to group 2 the number of increased exponentially. This observation provoked the question, is DG placement next to the substation always the most optimal location.? When taking in the consideration the life span for the LTC, no it is not. Though the auto-switch capacitor saved 18 operations, the LTC experienced 191 more operations in group 5 with the auto capacitor than it did in group 2 where the solar was located far from the source.

Table 7 Group 5 Results

	Double Circuit Length - DG Near Source											
	Light Loading				**Medium Loading**				**Heavy Loading**			
PV Generation	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW
Taps without Capacitor	4	5	12	60	7	8	23	57	13	15	21	65
Taps with Capacitor	3	4	12	60	5	7	10	57	13	15	21	65
Capacitor Operations	1	1	0	0	1	1	1	0	1	1	1	1
									LTC operations saved in 48 hours:			**18**

4.6 Group 6: Quadruple Circuit Length – DG Near Source

The results for this group are shown in table 8. Group 6 show similar characteristic to group 5 except with an increase in tap changes. Compared to group 3 there was once again a significant increase in the overall number of tap changes. 230 additional tap changes were experienced with the auto-switch capacitor in group 6 than group 3. Even though more tap changes occurred the auto-switch capacitor was able to reduce 7 LTC operations.

Table 8 Group 6 Results

	Quadruple Circuit Length DG Near Source											
	Light Loading				**Medium Loading**				**Heavy Loading**			
PV Generation	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW
Taps without Capacitor	4	5	12	60	7	7	17	60	14	15	21	68
Taps with Capacitor	3	2	9	68	6	7	4	66	14	15	21	68
Capacitor Operations	1	1	34	25	1	23	1	25	1	1	1	0
									LTC operations saved in 48 hours:			**7**

4.7 Group 7: Original Circuit Length – DG Far from Source Adjusted BW on LTC from 2 to 4

The results for this group are shown in table 9. Group 7 and Group 8 were studies performed to see if the capacitor station would still be effective if the band width of the voltage regulators were doubled. The capacitor appeared to no longer be effective in reducing tap changes due to the band width of the voltage regulator now exceeding the bandwidth of the capacitor. The system in this case would always step the regulator before relying on the capacitor.

Table 9 Group 7 Results

	Original Circuit Length - DG Far from Source Adjusted BW on LTC from 2 to 4											
	Light Loading				Medium Loading				Heavy Loading			
PV Generation	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW
Taps without Capacitor	1	1	1	2	3	3	3	4	7	7	8	8
Taps with Capacitor	1	1	1	2	2	5	3	4	7	7	8	8
Capacitor Operations	0	0	0	0	1	1	0	0	0	0	0	0
# of Saved Taps without Capacitor	2	3	5	13	3	4	6	15	4	5	5	8
# of Saved Taps with Capacitor	2	2	3	9	4	1	4	9	4	5	5	10

4.8 Group 8: Original Circuit Length – DG Near Source Adjusted BW on LTC from 2 to 4

The results for this group are shown in table 10. Group 8 shows the effect of changing the band width of the voltage regulator when the solar farm is located at the substation. When changing the regulator band width the number of tap changes significantly decreased and the capacitor, like with group 7, was rendered ineffective.

Table 10 Group 8 Results

	Original Circuit Length - DG Near Source Adjusted BW on LTC from 2 to 4											
	Light Loading				Medium Loading				Heavy Loading			
PV Generation	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW	0MW	2.5MW	5MW	10MW
Taps without Capacitor	1	1	0	17	3	3	5	17	7	8	11	23
Taps with Capacitor	1	1	0	17	3	3	4	17	7	8	10	28
Capacitor Operations	0	0	0	0	0	0	1	0	0	0	1	1
# of Saved Taps without Capacitor	2	3	11	43	4	4	11	40	4	5	9	40
# of Saved Taps with Capacitor	2	3	11	43	4	4	11	40	4	4	10	35

CHAPTER 5

SUMMARY OF ANALYSIS & APPLICATION

When reviewing each of the 144 cases from groups 1 through 6 there is only one observation needed to address. Was the auto-switch capacitor effective in reducing the number of tap changes by the substation LTC when the solar farm is interconnected? After review, yes it did. Table 11 shows that what the solar farm was connected far from the substation the capacitor was effective 53% of the time and the auto-switch capacitor only negatively impacted the system 6% of the time. Table 12 shows similar results when the solar farm is located near the source. Combined, the auto-switch capacitor benefitted the distribution system 43% of the time and only negatively impacted 6% of the time as seen in Table 13.

Table 11 Solar Farm Far from Source Summary

Far Source Summary		
Capacitor Switcher Benefitted Taps	**Capacitor Switcher Had No Effect**	**Capacitor Switcher Negatively Impacted Taps**
19	15	2
53%	42%	6%
94%		

Table 12 Solar Farm Near Source Summary

Near Source Summary		
Capacitor Switcher Benefitted Taps	**Capacitor Switcher Had No Effect**	**Capacitor Switcher Negatively Impacted Taps**
12	22	2
33%	61%	6%
94%		

Table 13 Combined Summary

Combined Summary		
Capacitor Switcher Benefitted Taps	**Capacitor Switcher Had No Effect**	**Capacitor Switcher Negatively Impacted Taps**
43%	51%	6%
94%		

As for group 7 and group 8, the data is not conclusive when adjusting the voltage band width. A more targeted model specifically focused on the adjustment of voltage band widths would need to be performed to determine its effect on limiting tap changes when functioning in tandem with an auto-switch capacitor station. The location of the solar farm plays a huge role in how the LTC will step to accommodate fluctuations in voltage. As seen from chapter 4, when the solar farm is placed near the source the LTC tends to tap more frequently with changes in generation. However, the LTC sees the true impact from the addition of an auto-switch capacitor station when the solar farm is located further downstream. Before placing all solar farms downstream though, it is important to analyze the system to ensure it will remain stable with the addition of the solar farm. It was witnessed on six occasions that the dynamic generation caused system instability.

CHAPTER 6

COST ANALYSIS

6.1 Introduction to Cost Analysis

There would be no purpose in proving that an auto-switch capacitor can reduce tap changes unless there is financial benefit to be gained from reducing LTC tap changes. As mentioned in the literature review, excessive tap changing for the LTC can result in additional maintenance costs and/or transformer failure. Both are large expenditures and can make or break a maintenance budget. This cost analysis will review the cost to replace an LTC, maintain an LTC, replace a substation transformer, install a substation transformer install a capacitor station, as well as various other expenditures that could incur with the inspection or failure of one of these units.

A disclaimer should be mentioned prior to continuing. The information provided in the following sections were collected from multiple sources. It is important to review the correct corresponding source to guarantee accuracy with information presented. The dollar values provided may no longer be valid due to inflation or material/equipment discontinuation.

6.2 The Substation Transformer

The substation transformer is often the most expensive of all single units in a distribution power system. The transformer foundation and materials needed to connect the transformer could cost approximately $150,000. The transformer itself could be as much as $900,000 to $1,200,000 thus making a to substation transformer 1.25 million dollars [16]. A separate report states that some transformers cost over $2,000,000 [17].

Yearly inspection and basic maintenance costs of a substation transformer was estimated to be as much a $2,499. This maintenance includes a Dissolved Gas Analysis (DGA) and visual inspection [18]. DGA were to show LTC contact fatigue then additional maintenance on the LTC would be done. The cost of that maintenance is in the following section. If the DGA shows the oil is not longer within acceptable tolerances it must be changed. The cost to filter oil in a substation transformer is approximately $20,000 [19].

6.3 Initial Load Tap-Changer Cost

To maintain a load tap changer if caught before failure can range from $77,000 to $97,000 per multiple bids within [20]. A full LTC replacement can be as expensive as $310,000 [21]. Though prices may vary throughout different territories it is astonishing that one group of parts could cost as much as a third of the total cost of the substation transformer to replace.

6.4 Initial Capacitor Bank Cost

To purchase the equipment for a new capacitor station would approximately cost $10,000 to $15,000 depending on the voltage and type of controller purchased [22]. From experience the installation cost of a three-phase controlled capacitor station is closer to $8000. Maintenance for these units depend on the utility and for the most part is negligible in cost.

6.5 Life Cycle Value Analysis

The lifespan of these units is difficult to track due to a multitude of variables that could impact these devices. However, IEEE and the International Electrotechnical Commission (IEC) have specific requirements and expectations for these units. The capacitor station, according to the IEEE Gold Book, will last 5.8 years before it fails [23]. At a cost of $8,000 and discount rate of 5% the present value cost of the capacitor is $6,028.26. The yearly cost for one unit is $1,004.71.

The LTC's life span is based on the number of tap changes in a year. IEC standard 60214-1 requires that an LTC's contacts is to have an effective life for at least 50,000 tap changes [24]. ABB performed testing on their tap changers and found that if the tap changer is on average 80% loaded it will not fail until after 300,000 tap changes for its UCL contacts and 400,000 tap changes for its UCG tap changes [25]. Thus, making the cost per tap change $6.66 and $5.00 respectively (if starting cost of transformer is $2,000,000.00). The cost per tap change if the minimum value is deemed the number of useful tap changes is $40.00.

If we compare our group 1 and group 4 results which represent our standard IEEE test feeders, we can see that the number of tap changes saved when the solar farm is placed far from the substation is 14 tap changes in two days among the 9 cases with the solar farm for an average of 1.56 tap changes every two days saved. Group 4 did not have as positive results and only saved 2 tap changes among the cases for an average of 0.222 saved operations in two days when the solar farm is placed at the substation. If the expected life of the LTC is the minimum required by the IEC, then the value saved by reducing the tap changes is $11,388.00 when the solar farm is far from the substation and only $1,620.60 when the solar farm is near the substation. If the LTC survives for a total of 400,000 tap changes then the value of the taps saved per year is $1,423.50 and $202.57 respectively.

When comparing the annual value of the capacitor station compared with the value saved by the capacitor offsetting the tap changer a total value of $10,383.29 is saved when the solar farm is far from the substation. When the solar farm is near the substation a total value of $615.89 is gained annually. This is if the LTC only survives 50,000 operations. However, if the LTC survives 400,000 tap changes the value saved is $418.79 and -$802.14. In three of the four cases a positive annual savings is experienced. Depending on the circuit and the system parameters, a significant cost savings can be experienced by the addition of the switch-bank capacitor.

CHAPTER 7

CONCLUSION & FUTURE WORK

The purpose of the research presented was to reduce the number of tap changes experienced by a substation LTC when a DG is interconnected downstream through the utilization of an auto-switch capacitor bank. To do this, IEEE 13 bus was modeled, and two different solar farm locations were analyzed. Along with the solar farms, three different circuit loadings and four different generation outputs were used. Finally, the length of the circuit was doubled and quadrupled to realize the impact of circuit length on system voltage stability. A cost analysis of the different devices used was presented to give the audience a realization of the potential cost savings when installing an auto-switch capacitor station.

The auto-switch capacitor station does in fact reduce the number of tap changes made by the LTC when there is a solar farm interconnected with the system. At times the auto-switch capacitor even assisted the system to remain stable. The placement of the solar farm must be carefully considered as instability is a potential problem if placed further downstream.

7.1 Future Work

To advance this work further there are a few different items that can be done to test similar systems. One can change the type of DG and test models with different DGs and DG output characteristics. In the work presented a solar farm was used and two different locations for the solar farm was analyzed. A wind farm or fuel cells could be used to present a different generation output on the distribution system.

Modifying the band width of the voltage regulator and creating an optimization problem that incorporates a dynamic band width could add much more substance to this research. One could also modify the voltage thresholds for the capacitor station as well. If a communication system was developed between the LTC and the controlled capacitor a more optimal outcome is all but guaranteed.

One final modification that can be tested is reviewing how the auto-switch capacitor will react on different circuits. IEEE 13 bus system was used in this case. A different system may need addition LTCs to output preferred voltages to all parts of the circuit. A delta circuit may or may not change how the system reacts as well. One could also modify system nominal voltages to determine what system voltage works best at optimizing load tap changer optimizations.

REFERENCES

REFERENCES

[1] Mcfetridge, Bob. “How to Reduce Operations on Load Tap Changers at Distribution Substation Transformers.” *2014 IEEE PES T&D Conference and Exposition*, 2014.

[2] Schellhase, H.-U., et al. “Load Tap Changers: Investigations of Contacts, Contact Wear and Contact Coking.” *Proceedings of the Forty-Eighth IEEE Holm Conference on Electrical Contacts*. 2002.

[3] Senjyu, T., et al. “Optimal Distribution Voltage Control and Coordination With Distributed Generation.” *IEEE Transactions on Power Delivery*, vol. 23, no. 2, 2008, pp. 1236–1242.

[4] Ronay, Karoly, et al. “Contributions to a Grid Connected Distributed Renewable Energy System, in Distinctive Operation Modes.” *2017 International Conference on Modern Power Systems (MPS)*, 2017.

[5] Malekpour, Ahmad Reza, and Anil Pahwa. “Reactive Power and Voltage Control in Distribution Systems with Photovoltaic Generation.” *2012 North American Power Symposium (NAPS)*, 2012.

[6] Mcfetridge, Bob. “Zones of Voltage Regulation the Missing Zone.” *2014 IEEE PES General Meeting | Conference & Exposition*, 2014.

[7] Costa, Andre Moura Gomes Da, and Wadaed Uturbey. “Voltage Regulation Strategies for Distributed PV Generation.” *2017 IEEE Manchester PowerTech*, 2017.

[8] Choi, Joon-Ho, and Seung-Il Moon. “The Dead Band Control of LTC Transformer at Distribution Substation.” *IEEE Transactions on Power Systems*, vol. 24, no. 1, 2009, pp. 319–326.

[9] Jin, Shanhong, et al. “Optimal Strategy for Distribution System with PV Based on Voltage Violation Regulation.” *The Journal of Engineering*, vol. 2017, no. 13, 2017, pp. 1124–1128.

[10] Vitor, Tiago Soares, and Jose Carlos M. Vieira. “Optimal Voltage Regulation in Distribution Systems with Unbalanced Loads and Distributed Generation.” *2016 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, 2016.

[11] Payne, Caleb. “VOLTAGE REGULATION POWER QUALITY PROBLEMS FROM PHOTOVOLTAIC SYSTEMS DURING INTERMITTENT CLOUD COVER.” *White Paper:* Aug. 2014, pp. 1–4.

[12] Said, Sayed M., et al. “Comparison between Operating Modes of Distributed Generation on Voltage Profile and Stability of Distribution Systems.” *2018 IEEE Texas Power and Energy Conference (TPEC)*, 2018.

[13] Saghaleini, Mahdi, and Behrooz Mirafzal. “Reactive Power Control in Three-Phase Grid-Connected Current-Source Boost Inverter.” *2011 IEEE Energy Conversion Congress and Exposition*, 2011.

[14] Putra, Jimmy Trio, and Sarjiya. “Reactive Power Optimization of Distributed Generation for Voltage Regulation of Distribution Systems.” *2016 8th International Conference on Information Technology and Electrical Engineering (ICITEE)*, 2016.

[15] Farag, Hany E., et al. “A Two Ways Communication-Based Distributed Control for Voltage Regulation in Smart Distribution Feeders.” *IEEE Transactions on Smart Grid*, vol. 3, no. 1, 2012, pp. 271–281.

[16] Wall, Darden Lee. “Parametric Estimating for Early Electric Substation Construction Cost .” *University of Texas*, 2009, repositories.lib.utexas.edu/bitstream/handle/2152/ETD-UT-2009-12-455/WALL-MASTERS-REPORT.pdf?sequence=1&isAllowed=y.

[17] Borough of Madison. “BOROUGH OF MADISON STRATEGIC CAPITAL PLAN.” https://www.rosenet.org/DocumentCenter/View/1377/Electric-Capital-Asset-PDF. 2014.

[18] Southern California Edison. “2018 General Rate Case.” *Southern California Edison*, 1 Sept.2016,www3.sce.com/sscc/law/dis/dbattach5e.nsf/0/F003E348D2A9C9FF8825802100665C05/$FILE/SCE02V06.pdf.

[19] Allen, Jon, and Anthony J. Picagli. “Taking Leaks Seriously.” *Transmission & DistributionWorld*, 2 Feb. 2017, www.tdworld.com/substations/taking-leaks-seriously.

[20] St. Charles. “Recommendation to Award Purchase Order for Substation Transformer Load Tap Changer Maintenance to SPX Transformer Solutions.” *Stcharlesil.gov*, 2016, www.stcharlesil.gov/sites/default/files/meetings/2016/attachments/a01-25-16-17553-13745.pdf.

[21] Horowitz, Kelsey, et al. “The Cost of Distribution System Upgrades to Accommodate Increasing Penetrations of Distributed Photovoltaic Systems on Real Feeders in the United States.” *National Renewable Energy Laboratory*, 2018, www.nrel.gov/docs/fy18osti/70710.pdf.

[22] Phipps, Jim. “How much do capacitor banks cost (an estimation for 1MVAR)? Are they used in every substation or at certain substations?” 19 Apr. 2018, https://www.quora.com/How-much-do-capacitor-banks-cost-an-estimation-for-1MVAR-Are-they-used-in-every-substation-or-at-certain-substations.

[23] IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems. Institute of Electrical and Electronics Engineers, 2007.

[24] IEC 60214-1:2014, Tap-changers – Part 1: Performance requirements and test methods

[25] On-load tap-changers, type UC Technical Guide. ABB, 2014. https://library.e.abb.com/public/2f37664d29e7403a9658e9495a1019d0/1ZSC000562-AAW%20en%20Rev%202_low%20res.pdf.