2018

Voltage regulation of unbalanced distribution network with distributed generators through genetic algorithm

Islam Ali
University of Northern Iowa

VOLTAGE REGULATION OF UNBALANCED DISTRIBUTION NETWORK WITH

DISTRIBUTED GENERATORS THROUGH GENETIC ALGORITHM

An Abstract of a Dissertation

Submitted

in Partial Fulfillment

of the Requirements for the Degree

Doctor of Industrial Technology

Approved:

_____
Dr. Hong Nie, Committee Chair

_____
Dr. Patrick Pease
Interim Dean of the Graduate College

Islam Ali

University of Northern Iowa

July, 2018

ABSTRACT

Energy demand has rapidly increased since the manufacturing revolution in the 19th century. One of the higher energy demands is electricity. The great majority of devices in the manufacturing field run on electricity. The vertically integrated grid paradigm has to be changed to supply the increase in the electrical demand residentially and commercially. Distributed generators (DG) such as Photovoltic (PV) is used to supply the increase in the electrical demand. Photovoltaic (PV) is one of the fast growing distributed generators (DG) as a renewable energy source. However, installing many PV systems to the distribution system can cause power quality problems such as over voltage. This would be more concern in an unbalanced electrical distribution network where nowadays most of the PV systems are connected. PV system should coordinate with other DGs and already existing voltage regulators such as on load tap changer (OLTC) on voltage regulation so that they can support the electrical grid without adding voltage problems. This dissertation focuses on voltage regulation of unbalanced distribution system through the utilization of PV reactive power feature by minimizing the system losses using genetic algorithm. The proposed method provides a single phase controlled PV system that regulates each phase voltage individually and focuses in maintaining the voltage for each phase within a certain limit. In addition, this study proposes a single-phase OLTC control by changing the tap position individually using loss minimization. The proposed algorithm is implemented in Matlab and Simulink. Results show that the PV reactive power can be utilized to control the system voltage as well as to minimize the traditional voltage regulator operations.

VOLTAGE REGULATION OF UNBALANCED DISTRIBUTION NETWORK WITH

DISTRIBUTED GENERATORS THROUGH GENETIC ALGORITHM

A Dissertation

Submitted

in Partial Fulfillment

of the Requirements for the Degree

Doctor of Industrial Technology

Approved:

_____

Dr. Hong Nie, Committee Chair

_____

Dr. Sadik Kucuksari, Co-Chair

_____

Dr. Shahram VarzaVand, Committee Member

_____

Dr. Mark Ecker, Committee Member

_____

Dr. Paul Shand, Committee Member

Islam Ali

University of Northern Iowa

July, 2018

ACKNOWLEDGEMENT

I would like to thank the University of Northern Iowa (UNI) for providing me this opportunity to study and do this research. I would like to thank Dr. Hong Nie, the chairman of my committee, for his support throughout all of these the years, since I started my Masters degree in 2010. I would like to thank Dr. Sadik Kucuksari, my co-chairman and mentor, for his support and guidance. He spent a great deal of his time coaching and guiding me throughout this research. His experience in research and writing technical papers taught me more than I could have imagined. These skills will stay with me for the rest of my career. I would like to thank Dr. VarzaVand for his support throughout my degree. I took several classes with Dr. VarzaVand and I learned a great deal from him inside and outside of academia. I would like to thank Dr. Mark Ecker and Dr. Paul Shand for their valuable input. Both of their contributions were imperative to the successful completion of this dissertation. I want to thank my committee members for their unyielding support.

I would like to thank all of my teachers who helped me to learn and reach my goals since I was young. I would like to thank everyone who gave me advice and supported and encouraged me. I would not have been here without all of this generous support.

I would like to thank my mother for all the sacrifices she made to raise me as a widowed mother. Even with all of the distance between us, she always supported and encouraged me. I would like to thank my late father for instilling the love of engineering and science in me at an early age. I did not spend much time with him, but the time we

spent together before his passing had a great impact on me. I hope he is proud of me. I want to thank my wife for her support and sacrifices during my study. You did a lot for me and it would not be possible without your support. You took care of many responsibilities, so I can focus on my study. I want to thank my daughters for their support and I hope I can be a good example to them. Watching them growing and smiling and playing encouraged me to do my best. I would like to thank my brothers for their support and guidance since I was young. I would extend my sincere gratitude to Dr. Fahmy and my aunt for their support and patience since I came to the United States. They always encouraged me and shared their experiences with me which served as great motivation. I would like to thank my uncle, Dr. Ahmed Metwali, and his wife, Dr. Nervana Metwali who stood by my family and me during a tense time. They were with my wife and kids at all the times I could not be. I would like to thank my family and friends back in Egypt. Thanks for the constant stream of encouragement. I would not make it without all of their support.

I remember sitting in Cairo International airport waiting for my flight to the United States. I did not know what I was doing and was contemplating whether I would succeed. In the eight years I have been here, I have learned so much about academia and in life. I have so many great memories that will forever be etched into my story. I would like to thank everyone who was part of this journey.

I hope this dissertation will be a good example for anyone believes that his/her dream is too far to be achieved. I, too, thought that was true one day.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

No table of figures entries found.

CHAPTER 1

INTRODUCTION

Background

Due to the increase of the electrical demand, the old paradigm of electrical power distribution has been changed in the last decade. In the old paradigm, the power is delivered only in one direction; from the power stations to the customers. With the increasing number of renewable energy sources utilization, the new paradigm includes distributed energy generators (DG) such as Photovoltaics (PV) and wind turbines at the customer side. Installing electrical sources in the customer side can improve the efficiency, performance, and voltage profile of the electrical grid (Alam, Muttaqi, Sutanto, Elder, & Baitch, 2012). In addition, the growing concerns on CO_2 emission can be minimized with the utilizations of PV that supports the electrical grid. PV is one of the fastest growing renewable energy industry. In 2012, the overall installed PV capacity exceeded 100 GW worldwide. In 2016, the overall installed PV capacity increased by 65% compared to 2012 to reach 165 GW worldwide (International Energy Agency, 2017). This number is expected to be increased in the next couple of years. By 2030, only Denmark will add around 3500 MW (Danfoss Group Global, 2013)

Nowadays, studies have been continuing on the electrical distribution system to implement this new bidirectional paradigm successfully. Having different types of electricity supply such as PV and wind turbines in the new bidirectional distribution system provide great benefits, however, they also bring some challenges. Figure 1 depicts a distribution system feeder where power may flow in two directions due to the delivery of the exceeding power of the DG to the grid. Since this bidirectional power flow is through the power lines, current generated losses exist as heat dissipation and as a result

voltage drop occurs. However, in this bidirectional configuration, the voltage drop may not be observed at the end of the line as it exists in the traditional distribution system.

.
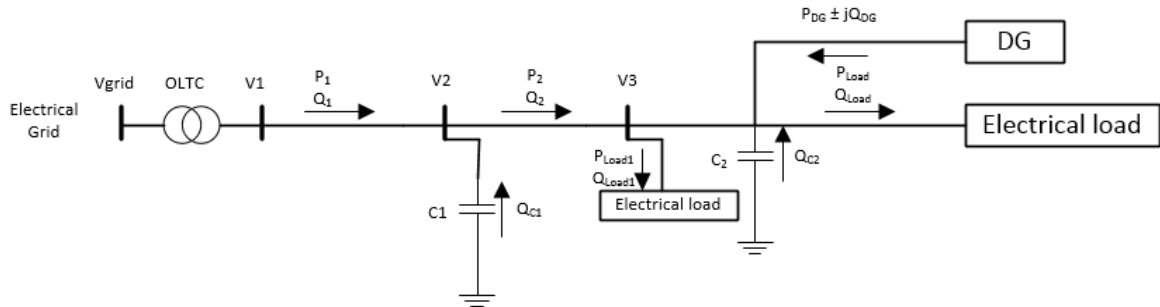
Figure 1. One line diagram for the electrical distribution system that includes DG at the load side. (Viawan, 2008)

The amount of voltage drop along the feeder is an important criteria to keep the electrical power system in stable operation. The grid voltage at each bus should be within a certain range in order to operate electrical equipment properly. In addition to the voltage drop concerns, increasing the use of PV can also cause some other problems such as overvoltage, voltage unbalance, and overloading of the line (Danfoss Group Global, 2013). This such variations in the system voltage can cause malfunctioning of the existing voltage regulators in the system such as capacitor banks and On-Load Tap Changing Transformers (OLTC). The unnecessary or frequent operation of these equipment can reduce their lifetimes and cause system failures resulting in power outages. This concern becomes more important as the PV system installations increase and highly varying electrical loads exist.

Reactive power in the electrical power system is useful to improve the voltage profile and as a result to reduce the power losses (Aggarwal & Yishengpan, 1989). As a tradition, capacitor banks are used in distribution system to support the voltage as passive elements. Due to the flexibility of the power electronic devices, DGs can be also be used to absorb and inject reactive power at Point of Common Coupling (PCC) for voltage regulation purposes. Reactive power amount can be controlled by the inverters that have the ability to generate lagging or leading current injected into the system. Reactive power is generated when the current and the voltage are not in phase.

The losses in the system mainly exist through the power lines that results with voltage drop over the transmission and distribution lines. In the old paradigm, the voltage drop increases towards the end of the line. Utility company needs to make sure that voltage stays within a range since all the electrical equipment are designed to work within a certain range of voltage (Hassaine, Olias, Quintero, & Haddadi, 2009). In the U.S., the electrical distribution system can operate within ± 5% of 110 volts (National Grid Electricity Transmission, 2010). One of the common approaches to keep the voltage within this range is using an OLTC transformer at the substation. If the voltage drops due to the high load demand, the OLTC will increase the line voltage to compensate voltage drop by changing its tap positions. When the voltage drop is not high at off-peak hours, the OLTC will reduce the voltage in the line (Turitsyn, Sulc, Bachaus, & Chertkov, 2011). Since typical power transformers have fixed turns ratios, they cannot maintain the voltage within limits during the peak hours, therefore, OLTC plays an important role in maintaining the voltage (Hu, Marinelli, Coppo, & Zecchino, 2016). Similar operational

principle exits for capacitor banks. They are connected to the PCC during the peak hours. They have the capability to generate reactive power to regulate the voltage at the PCC.

Statement of Problem

It is important to keep the electrical power grid voltage at each bus within a certain range in order to operate equipment properly. Increasing the use of PV can cause some problems such as overvoltage, voltage unbalance, and overloading. The variations in the system voltage can cause malfunctioning of the existing voltage regulators in the system such as capacitor banks and OLTC transformers. The unnecessary or frequent operation of these equipment can reduce their lifetimes and cause system failures results with power outages. This concern becomes more important as the PV system installations increase and highly varying electrical loads exist. The coordination between the PV systems and other DGs can improve the performance of the electrical grid and reduce the losses. In 2015, the U.S Energy Information Administration (EIA) mentioned in the annual report that transmission and distribution systems losses are around 5% of the total energy generated which costs the US around $9 billion annually (US Energy Information Administration, 2017).

Purpose of the Study

The purpose of this study is to provide a coordinated control method for the power systems voltage profile when high numbers of PV farms are connected to the electrical distribution system. It also provides an analysis of the unbalanced electrical distribution system voltage profile. In addition, it proposes solution to reduce the number

of tap changes in the OLTC in the unbalanced system that includes high penetrated PV systems. The proposed method provides coordination between different types of DGs to improve the voltage control equipment performance by reducing electrical losses. This study provides many optimal solutions to reduce the losses in the electrical distribution systems using Genetic Algorithm.

Need for the Study

Changing the vertically integrated grid paradigm to the bidirectional paradigm will increase the reliability and the robustness of the distribution system since there will be many distributed energy sources supplying the increased electrical demand in electrical grid from different locations. Improving PV's performance will help to maintain the voltage profile of the system and as a result reduce the number of tap changes for the OLTC at the substation. Reduce in the OLTC operation result with increase in the life time. Voltage regulation at each bus in the distribution system is highly important in order to increase the use of PV. All the electrical devices are designed to operate with a certain amount of voltage with a certain tolerance. Operating the electrical devices outside the acceptable range can reduce the life cycle of the equipment and in other cases can damage it. There are many ways to regulate the voltage at the PCCs such as capacitor banks, and load shedding. This study uses the reactive power control generated from the PVs to regulate the voltage at the PCCs. It also uses Genetic Algorithm (GA) optimization to find the optimal point of operation for each device.

Assumptions of the Study

The following assumptions are made during this study:

The surround temperature is not involved in any calculations. The overall efficiency of

100% the PV is used in the simulation. The output power of a PV has a linear relationship

with the temperature.

Research Question

This study will discuss the following research questions:

1. How can coordinated control improve the voltage profile of an unbalanced distribution

   system?

2. Would PV reduce the OLTC operation?

3. How can OLTC and PV system control unbalanced distribution system voltage?

4. How can GA optimize the distribution system to reduce the electrical losses?

Limitations of the Study

The following limitations are to be applied to this study:

1. The algorithm was implemented only in IEEE 13 bus system.

2. The price of the electricity generated by the PV is not considered.

3. The process time of the simulation is based on the Personal Computer (PC) used

   capability.

4. The inverters used in reactive power control characteristics are not considered.

CHAPTER 2

LITERATURE REVIEW

The studies in the history of PV systems yield growing implementations in power system in order to reduce the CO_2 emissions in the atmosphere. However, increasing PV installation can cause some technical challenges in the future which become more concern for the utility companies and system operators. This literature review presents the latest studies in reactive power control using PV and GA optimization in the distribution system. The literature review is classified in five categories as PV systems, inverters, reactive power control, OLTC, and GA.

<u>PV</u>

Photovoltaic is the scientific expression of converting the energy of the light to electrical energy. The word consists of two parts. Photo which is a Greek word means light. Voltaic is named for the famous scientist Alessandro Volta (Overstraeton & Mertens, 1986). The phenomena builds a voltage difference between two points which allow a direct current (DC) pass through the medium. The source of energy that is converted to electrical energy through the solar cells is the energy in the sun light. The output voltage varies according to the amount of light on the panel surface. The amount of power from the light could be measured using the solar irradiance. Solar irradiance is radiant power incident per unit area on the surface with a unit of W/m^2. There is a direct proportional relation between the output power from the PV system and the solar irradiance. In most cases, the peak power for the PV inverter is measured with $1KW/m^2$ at 25 degree centigrade.

Current- voltage (I-V) and power-voltage (P-V) curves describe the performance of the PV. They can be drawn as a variable with temperature or irradiance. Figure 2

provides the I-V curve with different irradiances. For each curve, the intersection with the

Y axis is the short circuit current which is the maximum current that the PV can supply in

case of short circuit at that specific irradiance level. For each curve, the intersection with

the X axis is the open circuit voltage which is the PV terminal voltage when there is no

load connected. The more irradiance the PV has the more current that can generate.
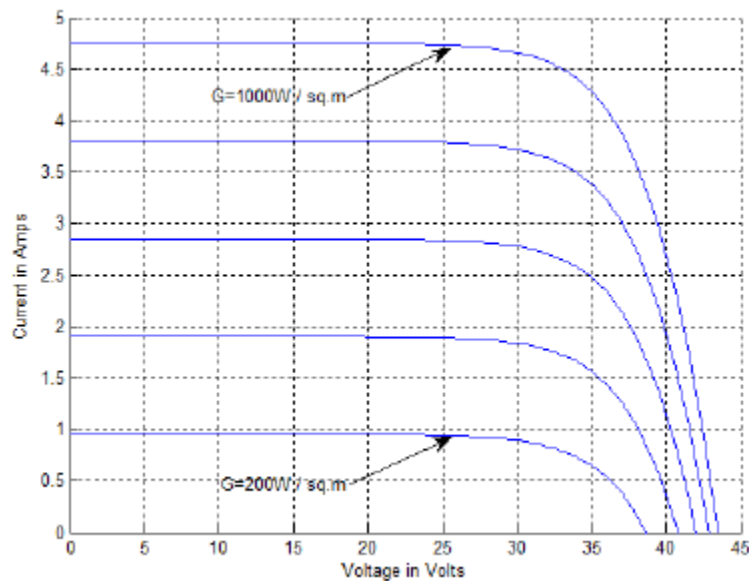
Figure 2. I-V curve with different irradiances Retrieved from (Jayakrishan, Kothari, Nedumgatt, Umashankar, & Vijayakumar, 2011)

P-V characteristic varies according to the irradiance as well. Figure 3 shows that

the more irradiance the PV has the more power it can generate. After a certain point the

power will drop even the voltage is increasing. The ideal operation point should be just

before the power drops.
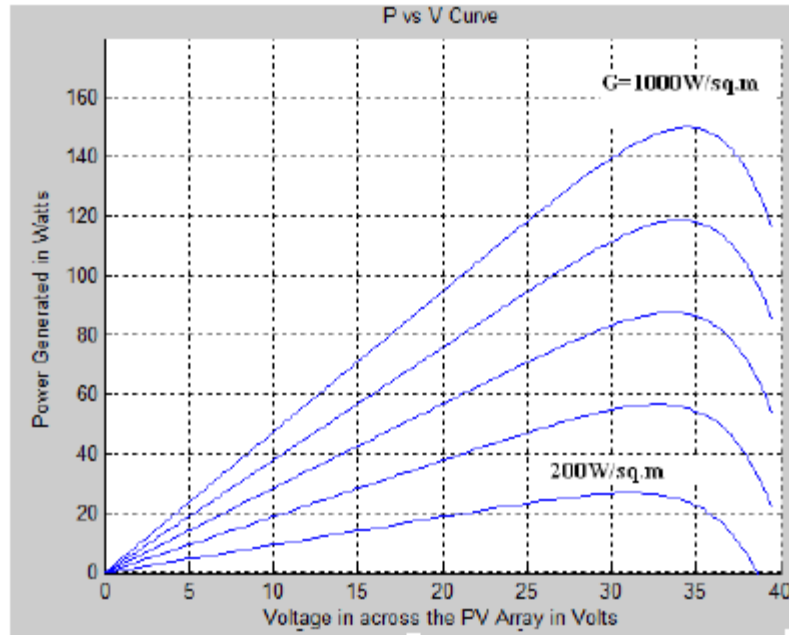
Figure 3. Power-Voltage curve with different irradiances. Retrieved from (Jayakrishan et al., 2011)

Figure 4 shows the relationship between the I-V and the surrounded temperature. Figure 5 shows the relationship between the P-V and the surrounded temperature. The higher the temperature in the surface of the PV, the lower the power that it can produce. A sunny day does not mean always more energy produced. There are several ways to reduce the temperature in the surface of the PV such as using light-colored materials help to reduce the heat absorption in the surface and water pipes under the surface of the PV for cooling.
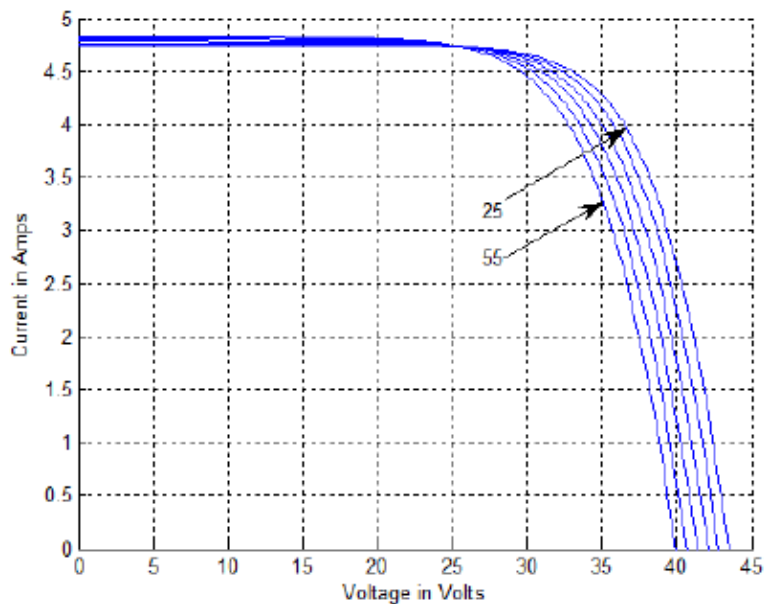
Figure 4. I-V curve with different temperature. Retrieved from (Jayakrishan et al., 2011)
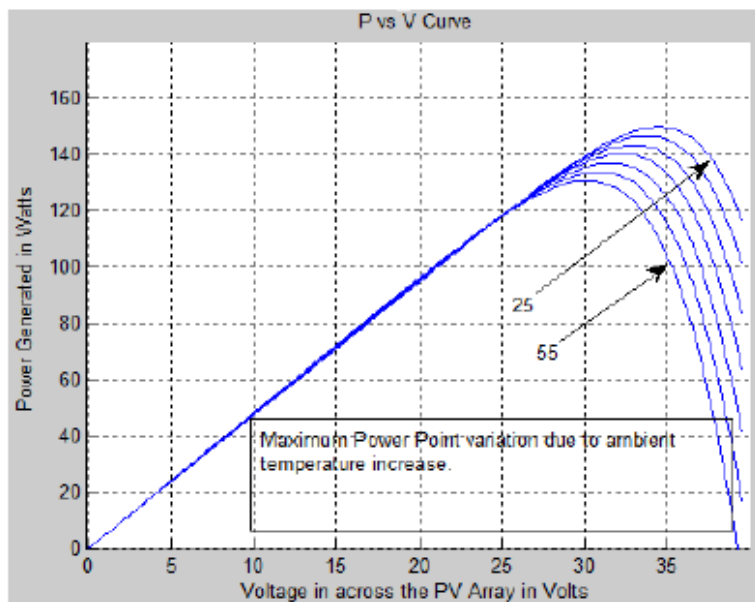
Figure 5. P-V curve with different temperature. Retrieved from (Jayasekara, Wolfs, & Masoum, 2014)

<div align="center">Inverters</div>

Inverter plays an important role in connecting the PV with the electrical grid. The inverter is responsible for converting the DC produced by the PV to Alternating Current (AC) to be connected to the electrical grid. There are different ways of connecting the PV to the inverters. It varies according to the applications, and number of PV. Different types of connection will be discussed as follows:

1. Centralized inverters.

This technique was common in the past, but it is not common nowadays. A large number of PVs are connected in series with a single phase inverter to establish a string to generate high voltage, and then many strings are connected in parallel to generate high power. There are some disadvantages of this approach such as a huge amount of high voltage DC cables are need to connect the PVs together, power loss because of the centralized Maximum Power Point Tracking (MPPT), harmonics, and power quality issues (Kjaer, Pederson, & Blaabjerg, 2005).

2. String Inverters and AC Modules.

This connection is the most common technique today. The approach is the modified version of the centralized inverter's approach where strings are not connected in parallel. Approximately 16 PVs are connected in a string and one inverter is used. The open circuit voltage can reach 720 V and the normal operation voltage can reach between 450 and 510 V. This approach increases the efficiency as the power loss is reduced (Kjaer et al., 2005).

3. Multi string inverters.

In this technique, each string is connected to a DC-DC converter to control the input voltage for the inverter. It is more efficient as each converter can control a group of PVs according to the needs. It provides flexibility to connect more PVs in the future unless the power does not exceed the maximum power of the inverter. It is easier to maintain as the operator can disconnect the converter and some PVs without effecting the operation of the others. The inverter is responsible to generate the appropriate voltage to be connected to the electrical grid. A feedback signal from the electrical grid is sent to the inverter to adjust the output voltage from the inverter. Many researchers are working in this approach because it has higher efficiency than others. Improving the respond time and the performance of the inverter will improve the whole system (Kjaer et al., 2005).

4. AC-Module Technology.

This technique is a standalone approach where each PV unit has its own inverter. These individual inverters are also called as micro-inverters which provides easy connection. Most of the PV units in this technique is not designed for high power generation. It is still expensive because of the technology used, but it is expected to be cheaper in the future as technology improves (Kjaer et al., 2005).

Reactive Power Control

Inverters are the key components that connect the PV with the AC grid through converting DC output to AC. By controlling the operation of the inverter, PV systems can inject or absorb reactive power. Voltage control in distribution system through reactive power generated by PV systems is addressed in many studies in the literature. In 2010,

Albuquerque, Moraes, Guimaraes, Sanhueza, and Vaz. presented an algorithm to control

the reactive power generation in PV. The algorithm used in inverter control is based on

two errors and one parameter. The first error between the PV DC output voltage, and

reference dc voltage. This error is used to control the active power in the PV inverter. The

second error between the PV current output and reference current is used to control the

reactive power. If the voltage grid is greater than 220V (nominal voltage), the system will

absorb reactive power. If it is less than 220V, the system will inject reactive power. PI

controllers are used to minimize the error as a result to control active and reactive power

(Albuquerque et al., 2010).

In 2011, Hamzaoui, Bouchafaa, and Hadjammar used fuzzy logic to control

Maximum Power Point Tracker (MPPT). A PI fuzzy logic regulator is used for the Pulse

Width Modulation (PWM). Power reference is calculated from a DC-bus voltage

controller to be used as a reference for MPPT. Error between the references and the

estimated feedback power are input to the hysteresis comparators. The authors created

look up tables for the reactive power error is at a certain level so that the PWM will have

an assured phase angle difference between the voltage and the current for reactive power

control (Hamzaoui et al., 2011).

Calderaro, Conio, Galdi, and Piccolo presented a method in 2012 called as

sensitivity method that controls the wind turbine output voltage through reactive power

control. In implementing the sensitivity, the maximum and minimum voltages have to be

identified so that the system runs within the safety voltage range. The system should be

running within the safety voltage range. ε is safety factor that defines the voltage control

area. In the flow chart, V_{act} is the actual voltage. V_{prev} is the previous reading for the

voltage. ΔV is the difference between V_{act} and V_{prev}. ρ_Q is the reactive sensitivity value.

If V_{act} is within the safety voltage range, the system does not change its operation. If V_{act}

is within the upper voltage control range, the system absorbs reactive power. If V_{act} is

within the lower voltage control range, the system injects reactive power. The amount of

the injected and absorbed reactive power depends on the voltage variation (Calderaro et

al., 2012).
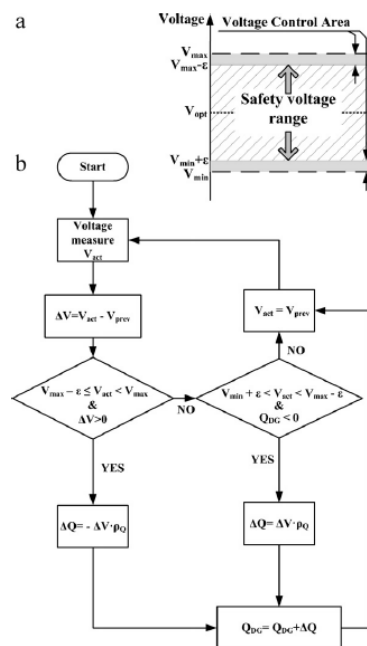
Figure 6. Sensitivity method (Calderaro et al., 2012)

In 2014, Yang, Yang, and Ma used injecting and absorbing reactive power

method to support the electrical distribution system during faults only. In normal

operation, the PV system generates active power only. They used the E.ON (European

energy supplier company) code for conduct. According to E.ON code the renewable

energy DG should follow a certain Voltage-time characteristics curve during the faults.

Figure 7 shows how the photovoltaic system should react during the fault. The system

should work above the curve. For example, the PV system should be connected to the

grid if the voltage drops to 0V for 150ms. If the voltage does not change after 150ms the

PV system should be disconnected.
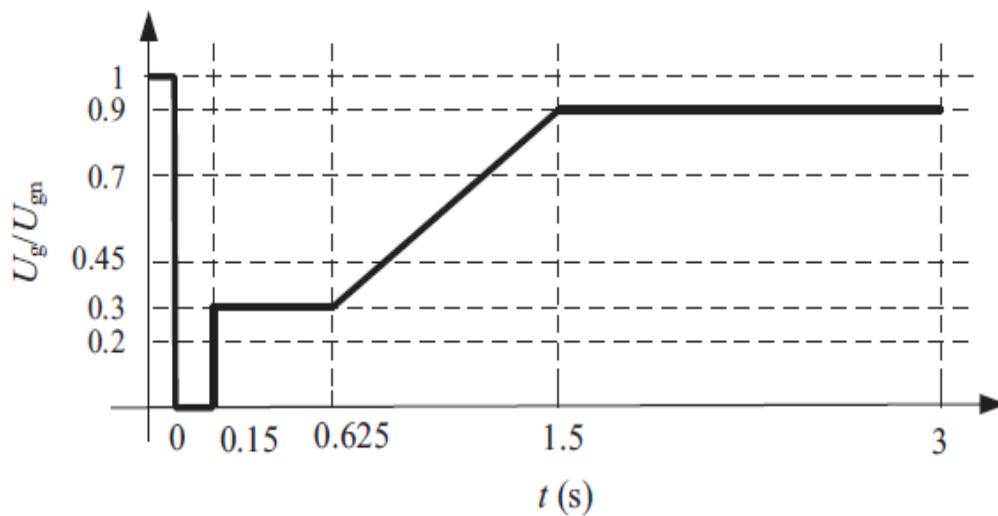
Figure 7. E.ON code during faults (Yang et al., 2014).

Once the fault is detected, the system will switch to non-MPPT mode. The system

generates the appropriate active power to keep the power balance in the system. The PV

system injects reactive power to support the electrical grid. The proposed method is

implemented in Matlab/Simulink and PV system can inject %100, %50, or %0 of its

maximum capacity for the reactive power. It depends on the voltage drop in the system.

In 2015, Chen and Salih presented an algorithm to control the reactive power injection using wind turbines. Matlab/Simulink and SymPowerSystems toolbox are used to control the operation of the distribution system. Three phase OLTC model is used. The simulation system is based on a rural 11 kV distribution system in Falköping, Sweden. As seen in Figure 8, the algorithm is based on changing the voltage deadband for each bus, which is the tolerance for the voltage, not changing the set point for the voltage of the bus. Most of the applications, the dead band is -+ 5%. Each wind turbine controls the voltage on the bus at Point of Common Coupling (PCC). OLTC is maintaining the voltage at the secondary side of it within a certain range and not communicating with any buses (Chen & Salih, 2015).
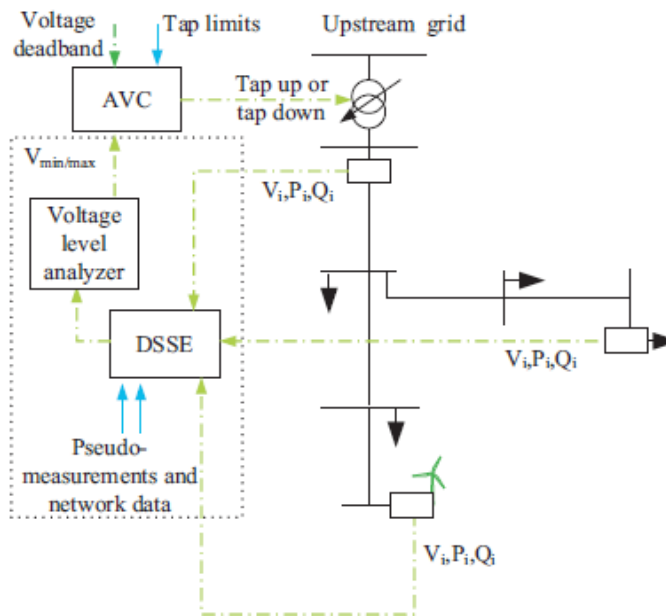
Figure 8. Control algorithm for the voltage regulation (Chen & Salih, 2015)

In 2015, Nazir, Kanada, Syafii, and Coveria used Newton-Raphson method to control reactive power. They calculated the values of *ma* (Index modulation) which is the amplitude of the inverter output voltage and alpha which is the grid phase angle. The turns ratio between the $V_{inv.}$ and $V_{supply.}$ is given as *a*. The inverter injects or absorbs reactive power based on *ma* and *alpha*. The amount of reactive power can be determined by the value of *ma* and the injection or absorption can be determined by the value of *alpha*. (Nazir et al., 2015).

$$G(ma, \delta) = Gi = \frac{(Vdc/\sqrt{2})amV}{X} \sin \delta - P = 0 \tag{1}$$

$$H(ma, \delta) = Hi = \frac{(Vdc/\sqrt{2})amV}{X} \cos \delta - V2/X = 0 \tag{2}$$

In 2016, Perera, Ciufo, and Perera from Australian Power Quality and Reliability Centre presented two algorithms to control the output power in PV system. The first algorithm is for injecting the active power that depends on the MPPT theory. The output power is controlled by the DC-link voltage and the output current of the PV. The second algorithm is to control the reactive power to maintain the voltage at the PCC within a certain level. Figure 9 shows the algorithm block diagram. V_{gm} is the peak value for the voltage at the PCC. V_{gm0} is the peak value for the reference voltage at the PCC. The error between $V_{gm.}$ & V_{gm0} is used to determine if the controller needs to adjust the voltage. K_{pq}/S block calculates the value for the $Q_{ref.}$ A limiter is used to define the maximum reactive power that the PV system can inject or absorb. $I_{qref.}$ is the reference for the reactive power current. $G_{cc}(s)$ is a filter used to calculate the peak value for the reactive

current output I_{gq}. $G_{vgq}(s)$ is the model for the Q algorithm controller. It is a close loop

control system where V_{gm} is measured all the time and used for as a feedback (Perera et

al., 2016).
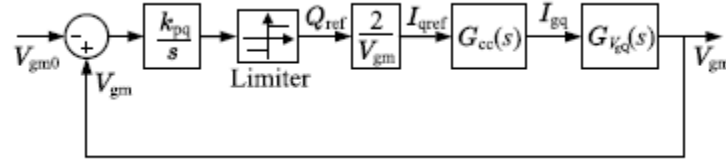
Figure 9. Q controller algorithm (Perera et al., 2016)

The authors provided two case studies to control the reactive power. The first case

is to inject a fixed minimum lagging power factor. The lagging power factor can be

maintained at 0.95. The active power changes according to the operation, and the

controller injects or absorbs reactive power to maintain the lagging power factor always

at 0.95. In this case, the PV does not generate the maximum output power all the time.

The minimum lagging power factor is used to minimize the losses and over loading. In

this case, the PV may be disconnected if the active power reached a certain level. The

second case is to generate the maximum apparent power. The active power changes

according to the demand, and then the PV inverter injects or absorbs reactive power until

it reaches the maximum apparent power for the PV system. In this case, the PV should

always be connected to the PCC to regulate the voltage.

In 2016, Rafi, Hossain, and Lu presented five different modes of operation for

voltage regulation with off-line-tap changer where the tap changer has to be disconnected

from the system to change the tap position. The system is a residential area in Australia

that includes three and single phase system, PV system, Battery Energy Storage (BES),

and Static Synchronous Compensators (STATCOM). Each PV system produces 4.5 KW

and 5KVA and supplies ten customers. If the PV generation is less than the electrical

demand, it operates in normal operation mode (mode A). The system is monitoring the

faults, and voltage level. The STATCOM and the BES are still available in mode A.

Mode B is when the PV generation is higher than the electrical demand and the PCC

voltage is greater than 1.06 per unit (pu) (over voltage case). The STATCOM works with

full capacity to regulate the voltage. If the voltage is still above 1.06 pu the BES starts to

charge the batteries. If the voltage still needs to be regulated, the system uses active

power curtailment approach. The last option is to shut down some particular PV sections

(Rafi et al., 2016).

Mode C is when the PV injects and absorbs reactive power. This mode was

implemented recently in some areas in Australia. It is cheaper than using BES

installations. The system is limited to either 0.95 or 0.90 lagging power factor operation.

The control system is based on the theory of de-rating power control. It means that there

is a limit for the active power which allows some capacity for the reactive power. Mode

D is to combine mode B and C together. The STATCOM regulates the voltage, then the

BES. The last option is to inject or absorb reactive power using PV. In addition to mode

D, DG power sharing is presented in Mode E. In power sharing, all the DGs share the

loads based on the power rating for each DG. The system was designed using

PSCAD/EMTDC (Rafi et al., 2016).

In 2014, Jung, Onen, Arghandeh, and Broadwater designed an algorithm to minimize the losses in the electrical distribution system using optimization. As seen in Figure 10, in the beginning of the simulation, the algorithm disconnects all the PVs then tries to determine the settings for the capacitor banks and voltage regulators. If the algorithm could not find the settings that keep the voltage within the acceptable range, it will run the simulation again. If the answers were found, then it will connect the PVs again and determine the control settings for the PV. By disconnecting the PV, the algorithm determines the voltage reference for the operating point. The voltage reference is used to find a better operating point by adjusting the voltage regulators (Jung et al., 2014).
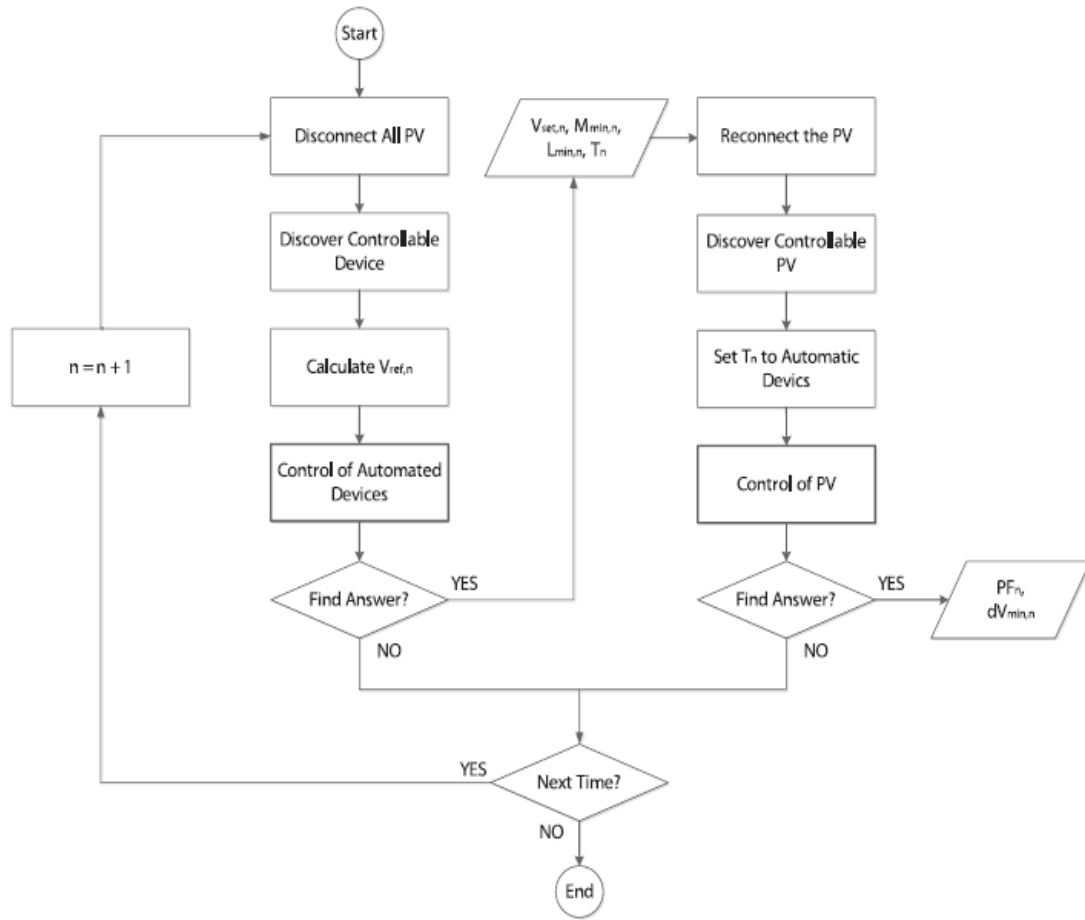
*Figure 10.*Flow chart for the optimization algorithm (Jung et al., 2014).

The objective function is to minimize the losses. The losses in the distribution system are calculated by equation 3.

$$L_n = \Sigma \sqrt{P^2_{Loss,i,n} + Q^2_{Loss,i,n}} \qquad (3)$$

Where

$P_{Loss,i,n}$ is the active power loss of each component.

$Q_{\text{Loss,i,n}}$ is the reactive power loss of each component.

There are three constraints in this study. The tap position, voltage in each bus, and the power factor should be within a certain range. The software used to optimize the system was not mentioned.

In 2016, Haque and Wolfs provided more options to regulate the voltage during high PV penetrations. They presented the reconductoring as a possible method to regulate the voltage. Reconductoring depends on increasing the cross-sectional area of the feeder cables. Figure 11 shows reducing the line reactance X and line resistance R can reduce the voltage drop across the feeders. Increasing cross-sectional area of the cables reduces the values for X and R. Reconductoring is a very efficient method to regulate the voltage, but it is very expensive. This method could be valuable during the design for a new system, but most of the time it is not practical for an existent system.
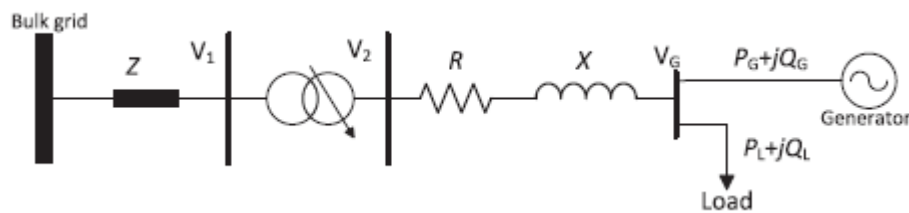
Figure 11. Single line diagram for a distribution system (Haque & Wolfs, 2016).

On-Load Voltage Regulator based on Electronic Power Transformer (OLVR-EPT) was presented in the Haque and Wolfs paper. It is a new technology to replace the OLTC which reduces the physical weight, harmonics, and voltage drop in the

transformer, provides faster and continuous voltage regulation, however, they are very expensive. There is no need to use mechanical tap changers in OLVR-EPT. Increased reliability and availability will encourage many companies to use it. There are other methods to regulate the voltage such as using fixed and switched capacitor banks, which is a common method has been used for years. Switching capacitors are used in discrete a step that means it is on or off state. The reactive power demand changes continuously and the whole capacitance value might not be needed (Haque & Wolfs, 2016).

The Haque and Wolfs paper provided coordination method between the power station utilities equipment and the PV. The method is based on using batteries. The voltage rises during the off-peak hours. The coordination controller sends a signal to charge the batteries to absorb the reverse power. The voltage drops during the peak hours. The coordination controller sends a signal to discharge the batteries to maintain the voltage within a certain level. This paper also presented the reactive power control in the PV system. It presented an algorithm to maintain the voltage at the PCC within an acceptable range. The algorithm is based on generating the maximum active power from the PV and using the rest of PV's capacity to generate the reactive power. The system was simulated in a small scale using a Texas Instruments floating point TMS320F28335 Digital Signal Processor. The reactive power is limited as the active power is maximum in all cases of study (Haque & Wolfs, 2016).

<u>Genetic Algorithm</u>

Genetic Algorithm is one of the optimization techniques. It is based on the theory of genetics and natural selection. GA was developed by John Holland in 1975. In 1989,

David Goldberg used GA to solve the problem with the gas-pipeline transmission control. It was the first time to use GA to solve a control problem (Haupt & Haupt, 2004). GA is not the best technique to solve all the optimization problems. There are some advantages of using GA such as:

- Can optimize continuous or discrete variables.

- Can solve a large number of parameters.

- Can run with parallel computers.

- Can optimize complex systems.

Objective function is the function that the GA is trying to minimize or maximize. GA generates some random potential solutions to solve the objective function. The solutions are called the chromosomes. Each chromosome contains number of genes to define the chromosome and explain its characteristics. The chromosomes that do not optimize the objective function will be eliminated. The chromosomes that optimize the objective function will generate another generation to optimize the objective function by reproduction (Ramos, 2014).

In 2011, Riffonneau, Bacha, Barruel, and Ploix used the optimization process to reduce the operation costs by managing the power flow and using PV systems and energy storage batteries as a power system application of optimization. In this study, the forecast data for irradiance, temperature, and loads consumption profiles were used to manage the power flow. The objective function of this study is:

$$CF(\Delta t) = [Pgrid(\Delta t) \times FIT(\Delta t) \times \Delta t] + [Pgrid(\Delta t) \times EgP(\Delta t) \times \qquad (4)$$

$$BrC(\Delta t)]$$

where

CF is cash flow.

P_{GRID} power grid.

FiT feed-in tariff.

EgP electricity grid price.

BrC the battery's replacement cost.

There are five constraints for the objective function:

$$P_{GRID}(t) = P_{PV}(t) + P_{BAT}(t) + P_{LOADS}(t) \qquad (5)$$

$$SOC^{min} \leq SOC(t) \leq SOC^{max} \qquad (6)$$

$$P_{BAT}^{min} \leq P_{BAT}(t) \leq P_{BAT}^{max} \qquad (7)$$

$$SOH(t) \geq SOH^{min} \qquad (8)$$

$$P_{GRID}(t) \leq P_{GRID}^{max} \qquad (9)$$

where

P_{PV} the output power from PV

P_{BAT} the output power from battery

P_{LOADS} total power for the loads.

SOC state of charge, which shows how much charge the battery has. 0% is empty.

100% is full.

SOH state of health. It is the condition of the battery compared to the ideal

condition. The ideal condition is a 100% at the time of manufacture.

The Riffonneau et al. study was implemented using RT-Lab HILBox 4U that can handle real-world interfacing using fast input/output boards for hardware-in-the-loop applications. The simulation was implemented using Matlab/Simulink where some RT-Lab blocks were used. This study did not control reactive power in the PV system. It was listed as a future work (Riffonneau et al., 2011).

In 2012, Kolenc, Papic, and Blazic designed an algorithm to minimize the OLTC operation and the losses in the distribution system based on an operating point which is the ratio between the reactive power and the active power generated by a DG. The operating point has to be ± 3 %. The algorithm searches for the optimal operating point for each feeder to make sure that the voltage does not exceed 1.05pu or below 0.95 pu. A load forecast is running with the simulation to determine if it is economically effective to change the tap position. The algorithm has been simulated by DIgSILENT Power Factory simulation program and MATPOWER. 20 kV medium-voltage Slovenian distribution system was used to test the algorithm. OLTC controls $\pm 12\%$ of the rated voltage with 1.33% for each tap position (Kolenc et al., 2012).

In 2014, Ramos used GA to optimize the operation of distributed generation. The objective function is the power losses in the system. PV systems were used to inject or absorb reactive power to minimize the power losses. The objective function of Ramos study is:

$$P_{\text{loss}} = \sum_{k=1}^{nb} Gk[V_k^2 + V_m^2 - 2V_k V_m \cos(\theta k - \theta k)] \tag{10}$$

where

nb the number of branches.

P_{loss} the power loss.

G_k is the conductance of the line.

V_k & V_m are the voltage at bus k and m.

θ_k & θ_m are the phase angles at bus k and m.

The Ramos study had only one constraint for the reactive power injection and absorption. The reactive power is limited between 0.95 inductive and 0.95 capacitive. OLTC was not part of the objective function. MATLAB is used to optimize a modified IEEE system (Ramos, 2014).

In 2014, Yang et al. presented an algorithm to minimize the losses in the distribution system. The simulation was implemented using Visual Studio C++ and multi-phase distribution network model UBLF. CPLEX solver was used to solve the optimization problem. The optimization was designed as a mixed integer quadratic optimization problem. The algorithm was tested and verified for nine different distribution systems. The distribution systems were divided into two categories. The first one includes control the reactive power using capacitors. The second one includes capacitors and reactive power generated from different DGs. OLTC was not part of any distribution systems. The objective function is to minimize the losses by reducing the active and reactive current as seen in equation 11.

$$\text{Min } F = \sum_{i=1}^{nb}\left\{\left(I_i^d\right)^2 + \left(I_i^q\right)^2\right\} \times r_i \tag{11}$$

Where

I_i^d, I_i^q is the active and reactive current in branch i.

r_i is the resistance of branch i.

The constraints in the Yang et al. study include a limitation for the current, the voltage, the maximum reactive power, the minimum reactive power, the line-to-neutral voltage, and line-to-line voltage.

In 2016, Harnett used Frank – Wolfe algorithm to optimize the power flow in the electrical distribution system. The algorithm focuses on running the system safely when there is a problem in the electrical distribution system such as overvoltage, and faults. Harnett used MATPOWER for the simulation. The voltage regulation was done by existing voltage regulators such as capacitors and injecting reactive power using wind turbine and generators. Harnett also focused on using optimization to find the weakest point in the electrical distribution system. The weakest point is the point where if it has a failure, the failure can cause a black out and it will be difficult to recover. Harnett mentioned that knowing the weakest point in the grid will be very useful for the smart grid. Finding the weakest point can help to design the electrical grid so that it can handle some issues at the weakest point. Harnett did not regulate the voltage using PV and OLTC (Harnett, 2016).

<center>OLTC</center>

Transmitting electricity causes voltage drop over the transmission and distribution lines. The voltage at the beginning of the line is higher than the voltage at the end of the line when there is an inductive load that is the case for power systems. The longer the transmission line is, the more voltage drop in the end. All the electrical equipment is designed to work within a certain level of voltage (Hassaine et al., 2009). In the US, the electrical distribution system can operate within ± 5% of 110 volts (National Grid

Electricity Transmission, 2010). That means the equipment at the end of the distribution lines could face the risk of having voltage less than 110 volts. The common approach to solve this problem is using an OLTC transformer at the substation. It allows the transformer to adjust the voltage to keep the voltage within limits. If the voltage drops due to the load demand is high, the OLTC will increase the voltage in the line to compensate that voltage drop by changing its tap positions. At night when the voltage drop is not high, the OLTC will reduce the voltage in the line (Turitsyn et al., 2011). The peak times are in the morning when the residents are getting ready for work and in the afternoon when they come back from work. For the commercial areas, the peak time is around noon. If there is no work shift at night the electrical demand is low.

OLTC has been one of the main components in the electrical network for the past 90 years. It not only maintains the secondary voltage within a certain range, but also used for phase shifting. The main types of OLTC are high-speed-resistor type and reactor type. Resistor type is used in large transformers and reactor type is used in small transformers. The changer is installed inside the transformer. OLTC changes the turns ratio for the transformer by changing the tap position. The voltage could be increased or decreased based on the tap position. The tap change could be installed in the primary or the secondary side of the transformer. As show in Figure 12, the reactor or the resistance is used as a bridge to transfer the loads from one tap to another without any shutdown or interruption. During changing the tap position, the current is divided between two taps to reduce the probability of having sparks during the transition (Dohnal, 2013).
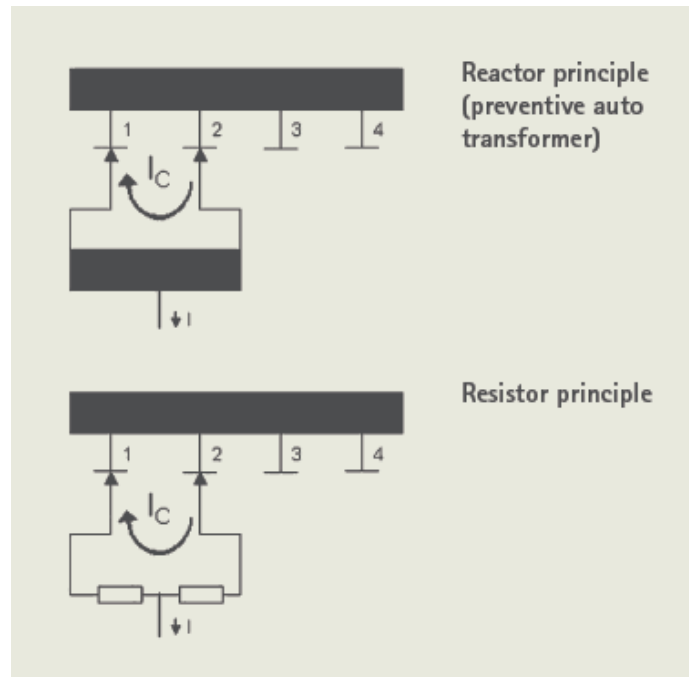
Figure 12. Reactor and resistor principle. (Dohnal, 2013)

Summary

In the literature review there are some researches that are focusing on reducing the power losses in the distribution system. In 2014, Ramos presented an algorithm to minimize the losses, but the OLTC was not involved in this simulation. In 2016, Perera et al. from Australian Power Quality and Reliability Centre presented an algorithm to reduce the power losses. The algorithm was limited to 0.9 lagging power factor and was not designed to operate with different lagging power factor. Some of the researches are designed based on forecasting data such as the study presented by Marko, Igor, and Boštjan. Any big change between the forecasting and actual data will cause inaccurate decisions. The study was designed to reduce the power losses as well.

Some other studies were focusing in maintaining the voltage within the acceptable

range without looking at the power losses in the distribution system. Albuquerque et al.,

2010 presented an algorithm to regulate the voltage using reactive power generated from

the PV system. They used PI controller to control the reactive power. Hamzaoui et al.

presented a fuzzy logic control system to regulate the voltage. The system was built to

regulate the voltage by changing the MPPT. There are some researches that present the

voltage regulation only under some circumstances such as the research presented by

Yang et al. in 2014. The PV regulates the voltage only during the fault condition in the

electrical system. If the fault is still exist after 10ms the PV system will be disconnected.

A three phase controlled system for the PV was presented by and Chen and Salih in 2015.

In their system, the decision to inject or absorb reactive power is based on one phase and

the change happens simultaneously for the three phases. In 2016, Rafi et al. used storage

batteries and STATCOM to regulate the voltage. When there is a small electrical

demand, the system charges the batteries. The charged batteries will be used during the

peak hours or when the PV cannot generate enough power due to low irradiance.

The literature review also presented some research using optimization in the

electrical distribution system. In 2014, Ramos used GA to reduce the losses in the

distribution system. The algorithm given by Ramos was three phase controlled system.

The above mentioned studies considered the voltage control of a distribution

system in many different aspects. Some considers the existing regulators and others

focused on the PV inverter control. However, there is limited studies exists that considers

coordination between the PV inverters and existing regulators and more specifically not for unbalanced distribution system.

This Dissertation proposes a coordinated control method between the existing regulators and PV inverters for the power system voltage profile when high numbers of PV farms are connected to the electrical distribution system. This study also provides an analysis and voltage regulation of the unbalanced electrical distribution system voltage profile. Mix integer nonlinear optimization problem is solved using genetic algorithm to define the PI controller parameters while not considering the details of power electronic devices. Matlab and co-simulation of Simulink are used to implement the algorithm on IEEE 13 bus unbalanced distribution system.

<div align="center">Scope of the Research</div>

Voltage regulation in unbalanced system has been investigated for many years. The researchers try to regulate the voltage generated from each source of energy connected to the electrical distribution. Implementing the bidirectional paradigm encourages the researchers to investigate how to use different sources of energy in voltage regulation. In the decade, using PV system in voltage regulation has been investigated. It has been tested and verified, but there are some gaps in this field such as no study to simulate a single phase controlled inverter for the PV system. In addition, there is no study to simulate single phase controlled OLTC. All the simulations have been done to control all the three phases simultaneously. There is no study that optimizes OLTC and PV system to reduce the electrical losses using GA.

This research provides a single phase controlled inverter PV model and a single phase controlled OLTC model. It provides an optimization system for OLTC and PV system using GA with the objective function of minimizing the line losses. All the simulations are done using Matlab/Simulink, and Simulation optimization.

CHAPTER 3

METHODOLOGY

There are many parameters that can be adjusted in the electrical distribution

system such as OLTC tap position, generator parameters, and capacitor bank switch

states to increase the stability and reduce the cost of operation through loss minimization.

Power systems uses optimization processes to find the optimum values for these

parameters to be a stable system. Optimization is a well-known method used in power

systems such as in unit commitment (Patriksson, Andreasson, & Evgrafov, 2017). In

addition, optimization is used commonly in control systems to find the best control

parameters for better response.

The proposed voltage control scheme is considered for an unbalanced distribution

system that includes OLTC, capacitor bank and PV systems at the user side. The method

utilizes PV system inverters to provide reactive power to the distribution system. In

addition, it considers the existing voltage control devices (OLTC and Capacitor)

operation and aims to keep their operations in minimum to increase their life time. The

voltage control of unbalanced network is achieved with single phase voltage control

where the individual line impedances are considered. By minimizing the overall system

losses, coordinated control of the OLTC and PV reactive power is achieved using Genetic

Algorithm for loss minimization. The PI controllers used to control reactive power of the

PVs are tuned through the optimization process. The proposed method is implemented

using Matlab Optimization Toolbox and co-simulation of Simulink model of IEEE 13 bus

system for more accurate and detail control and results. The following subsections

present the details of problem formulation and its solution as optimization.

<u>Unbalanced Distribution System Voltage</u>

The unbalanced distribution network and its voltage profile is analyzed using

IEEE 13 bus unbalanced distribution system test case. The network is modeled using

Matlab Simulink and the existing OLTC model. The PV reactive power control affect is

investigated by adding PV systems at different locations over the network where the

voltage drop is maximum. As seen in Figure 13, the base case voltage profiles show that

the system is unbalanced due to unequal loads connected to each phases. When the

regulation in the OLTC is disabled, the bus voltage is not within the acceptable range.

OLTC has to change the tap position to regulate the voltage when there is a change in the
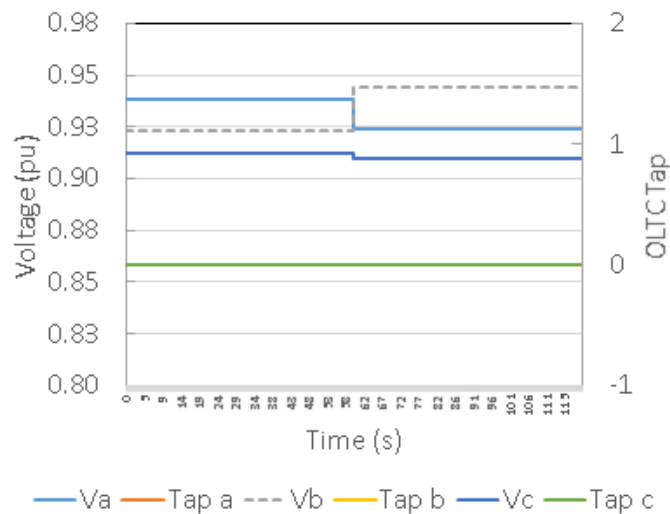
load amount.

*Figure 13.*Base case without voltage regulation (Bus 632)

As seen in Figure 14, the regulation in OLTC is enabled to maintain the voltage in bus 632 within the acceptable range. The OLTC has to change the tap position individually to regulate the voltage.
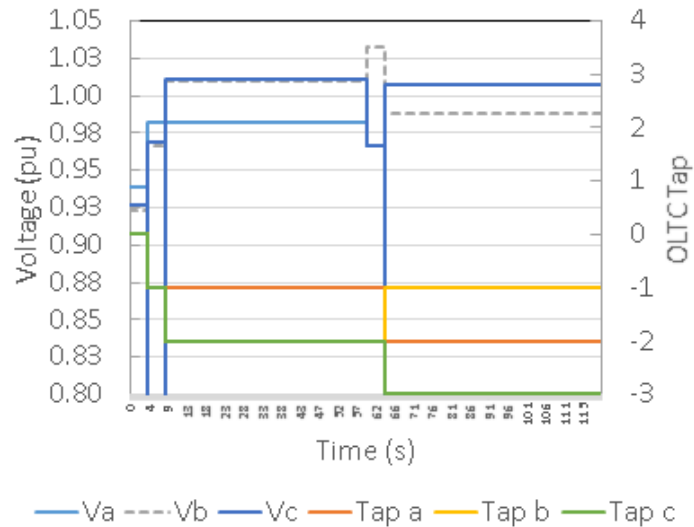
*Figure 14.*Base case without PV system (Bus 632)

In order to correct the voltages, the PV systems reactive injection features are added and OLTC model is modified by separating the three phase control to single phase control. The PCC bus voltages are kept at 1 p.u voltage by injecting required reactive power regardless of the PV reactive power capacity. PI controller is used for voltage control of individual phases to correct each phase voltages. This requires single phase PV system structure. Since the voltages are corrected at the PCC, the other voltages toward the substation are also stayed within the voltage limits. This also reduced the OLTC operation in the system. The study also investigated the wind turbine reactive power injection at the substation level.
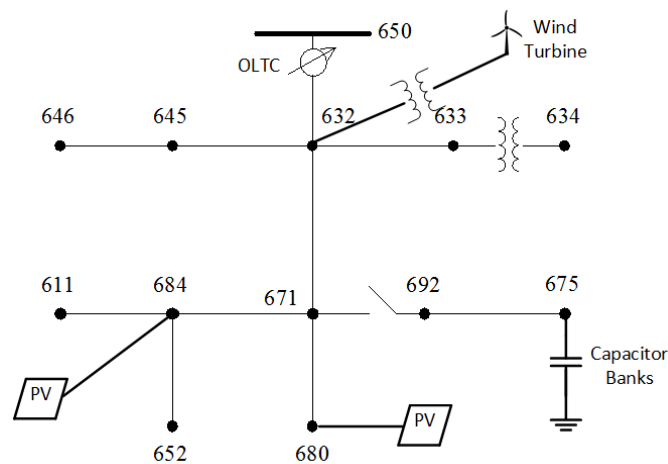
Figure 15. Modified IEEE 13 bus

The findings in this study are as follow (Ali & Kucuksari, 2016):

- Controlling reactive power generated by PV system reduces the OLTC tap changing.

- The reduction of OLTC operation is more efficient using single phase voltage control

  by OLTC and PV.

- Single phase control PV system can keep the voltage within an acceptable range in

  unbalanced distribution system, as long as it does not reach the maximum capacity.

<div align="center">OLTC and PV Model Modifications</div>

Single phase voltage control requires regulation of individual phase tap positions

of OLTC. The existing three-phase controlled OLTC model in Matlab Simulink is

modified to achieve single phase control. The Matlab provided model uses additional

windings on primary side and uses them as additive or subtractive windings to increase or

reduce the voltage on secondary side terminals as shown in Figure 16. The fixed voltage

difference ΔV between each tap positions times the number of tap provides the total

voltage difference that can be achieved and applied to the system. Through the turn ratio

of the nominal windings of each phase, the total voltage on primary is transferred to

secondary as follows (MathWorks, 2017):

$$\frac{V_2}{V_1} = \frac{1}{(1 + N.\Delta V)} \times \frac{V_{nom2}}{V_{nom1}} \qquad (12)$$
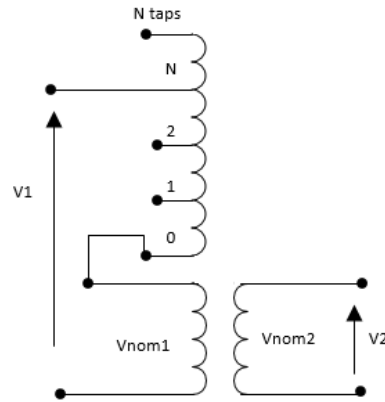
*Figure 16.*OLTC windings configuration (MathWorks, 2017)

From this relationship, the secondary side terminal voltage can be written as

$$V_2 = V_1 \times \frac{1}{(1 + N.\Delta V)} \times \frac{V_{nom2}}{V_{nom1}} \qquad (13)$$

The modified OLTC model utilizes this secondary side voltage for each phase for

loss minimization by eliminating the existing voltage control mechanism of the OLTC

model. In addition, the three phase windings are separated and individually controlled.

The PV model used in this study is the available model in Matlab Simulink. The model is also modified to inject reactive power. In addition, the three-phase designed model is converted to single-phase design and PI controllers for each phase are added to control the reactive power. The actual inverter model is not considered since the focus is not given to its control.

<center>Coordinated Voltage Control through Loss Minimization</center>

The voltage drop in power systems is mainly due the heat dissipated power I^2xR on the transmission and distribution lines. This is only the active power portion of the losses. There are system losses due to the reactive power as well. The losses are high in distribution system since the X/R ratio of the conductors is high and the current amount on these conductors is higher. In order to improve the voltage profile in the system, the minimization of the overall system losses is crucial. The total system losses are the sum of individual line losses which can be express as $P_{total\ loss} = \sum_{i=1}^{j} P_{ij}$ where j is the total number of line sections between the busses in the system. The individual line active power losses can be express as $P_i = I_i^2 \times R_i$ where I is the line current, i is the bus number, and R is the line resistance. Pi can also be expressed in terms of the bus voltage and line resistance as $P_i = \left(\frac{V_{i+1}-V_i}{|Z_i|}\right)^2 \times R_i$. Same relationship can be used to calculate the line losses for the line between i and $i+1$ where the OLTC secondary side is connected to bus $i+1$ as follows:

$$P_i = \left(\frac{V_{i+1} - V_i}{|Z_i|}\right)^2 \times R_i \tag{14}$$

$$P_i = \frac{(V_1 \times \frac{1}{(1 + N.\Delta V)} \times \frac{V_{nom2}}{V_{nom1}} - V_i)^2}{|Z_{Line}|^2} \times R_i \tag{15}$$

where V_1 is the OLTC primary side voltage and R_i is the resistance of the line between

busses i and $i + 1$.

The reactive power effects the line losses since the total current over the line has

active and reactive power components. The $P_i = I_i^2 \times R_i$ line losses can be written in

terms of active and reactive power flowing through the line as:

$$P_i = I_i^2 \times R_i = \left(\frac{S_i}{V_i}\right)^2 \times R_i = \left(\frac{\sqrt{P_i + Q_i}}{V_i}\right)^2 = \frac{P_i^2 + Q_i^2}{V_i^2} \times R_i \tag{16}$$

This relation shows that if reactive power is injected by a PV or capacitor as

negative Q, the line losses can be reduced since the total circuit current drops.

In order to minimize the system losses, Genetic Algorithm (GA) is selected as the

optimization algorithm since the power systems is a nonlinear system with several

constrains. The total loss that needs to be minimized becomes the fitness function for GA.

The decision variables for minimization are the reactive power amount of the PV, the

turn on and off state of capacitor if exists, and OLTC tap position all of which affect the

line losses as explained earlier. The system constrains during the minimization are the

voltage limits, reactive power capacity of the PV inverter, OLTC tap numbers, and

capacitor on and off states. The capacitor on and off states are binary, therefore, the

overall fitness function becomes a mix-integer nonlinear problem and can be formed for j

number of bus system as:

$$P_{Total\ loss} = min\left[\frac{(V_1 \times \frac{1}{(1+N.\Delta V)} \times \frac{V_{nom2}}{V_{nom1}} - V_2)^2 \times R_i}{|Z_{Line}|^2} + \sum_{i=2}^{j} \frac{P_i^2 + \left(Q_{L_i} \pm x_{ic}Q_{Cap_i} + Q_{PV_i}\right)^2}{V_i^2} \times R_i\right] \quad (17)$$

The system constrains are:

$$-N_{Tap} \leq N \leq N_{Tap}$$

$$x_{ic} = 0 \text{ or } 1$$

$$-Q_{PV_{imax}} \leq Q_{PV_i} \leq Q_{PV_{imax}}$$

$$0.95\ p.u \leq V_i \leq 1.05\ p.u$$

where

V_1 the grid voltage.

N the tap position in the OLTC.

N_{Tap} is the number of taps in the OLTC

ΔV is the voltage difference between two tap positions in the OLTC.

V_{nom1} is the nominal voltage in the primary side of the OLTC.

V_{nom2} is the nominal voltage in the secondary side of the OLTC.

R is the transmission line resistance of line.

P is the load power at bus.

Q_L is the load reactive power.

Q_{Cap} is the capacitor reactive power.

Q_{PV} is the reactive power generated by the PV.

The function that needs to be minimized has basically two parts; (1) the line right after the OLTC, and (2) the other lines. Although both parts are same lines in terms of construction, the difference is on the formulation of the losses. As it is clearly seen that the first part is a variable of the OLTC tap positions and the others are variable of reactive power of the PV and capacitor if exists.

In addition to direct control of PV reactive power Q_{PV_i} in the objective function, PI controller is used for dynamic voltage control of individual phases to correct each phase voltages. The error for the PI controller is determined by comparing the actual voltage with 1 pu reference voltage. The error is used as input for PI controller. The output from the PI controller is the reactive power injected or absorbed by PV that is used in the formulation. During the optimization, GA determines the values for K_P and K_I, as a result, the PI controller decides on reactive power amount to regulate the voltage either through injecting or absorbing reactive power. The PI controller generates the required Q as

$$Q(s) = (K_p + K_i \frac{1}{s})\, Error(s) \qquad\qquad (18)$$

K_P is the proportional constant.

K_I is the integral constant.

The proposed algorithm has been implemented in Matlab and Simulink. Matlab optimization toolbox, parallel pool toolbox, and Simulink Simpower systems toolbox are used for optimization through simulation. The flow chart given in Figure 17 shows the process flow. Optimization starts with initial values of zeros. GA generates the first

generation of the solutions which are the parents then updates the variables and runs the

Simulink model that works as a co-simulator. The objective function is formulated inside

the Simulink and integral of time-weighted absolute errors (ITAE; Chen & Xue, 2014)

method is used to minimize the errors. The simulation files run in parallel using the

Matlab parallel pool tool to reduce the simulation time. The Simulink file is a power

system simulation in phasor form where only the magnitudes of the signals are

considered. Once the simulation is completed, the calculated system losses and voltage

constrains are send back to the GA for comparisons and the next set of generations are

formed if needed. The iteration continues until the desired results meet. Simulation file is

updated with the final values and the system is simulated with the decision variables for

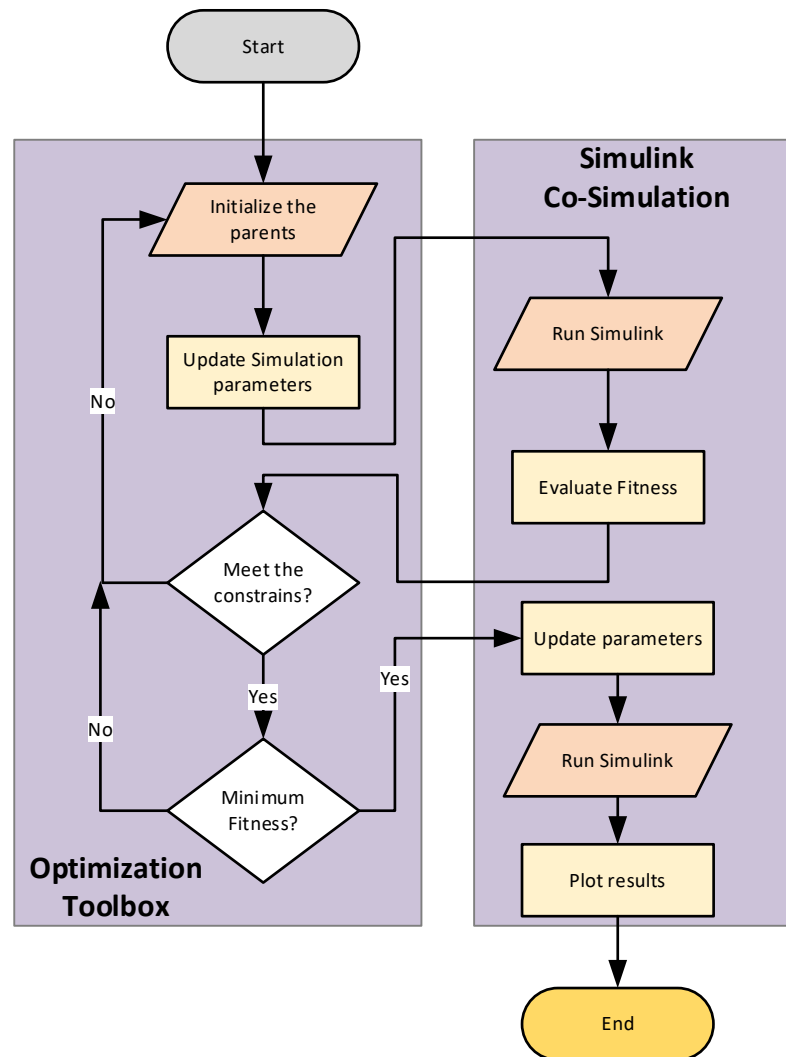final results.

Figure 17. Algorithm flow chart

<u>Test Cases</u>

In order to implement the proposed method, various test cases are used. In addition to a single feeder test system, IEEE 13 bus unbalanced distribution network test case is used (Ali & Kucuksari, 2016). The networks are modeled using Matlab Simulink with the modified OLTC and PV models. The original IEEE 13 bus test case model is

first developed as base case and simulated to verify that the system is unbalanced and voltage drops are observed. PV systems are added as three phase active power sources only. It is verified that the active power injection of the PV systems are not helping the voltage profile. In order to bring the voltage drops to desired range, the PV systems reactive power injection features are added and OLTC model is modified by separating the three phase control for positive sequence and single phase controls separately. The PI controllers' reference input are set to 1 since the PCC bus voltages are desired to be 1 p.u

The following three case studies are performed by the test system:

Case 1: Single feeder distribution system contains OLTC, PV, capacitor, and electrical load. The algorithm is controlling the reactive power generated by the PV, OLTC tap position, and the capacitor bank operation.

Case 2: PV system and capacitor bank connected to bus 675 of IEEE 13-bus system. The algorithm controls the system based on the positive sequence of unbalanced system voltage.

Case 3: PV system and capacitor bank connected to bus 675 of IEEE 13-bus system. The algorithm controls the system voltage as three single phase system.

Case 4: Dynamic load is added to bus 680 of IEEE 13 bus system used in case 3 and variable irradiance is implemented to the PV system.

.

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter discusses the cases of study and their results. It also provides some

analyses to the data and explains how the algorithm works in each case.

<u>Case 1</u>

A simple simulation study has been conducted using Matlab/Simulink to verify

the proposed method and its implementation. Figure 18 shows the three phase, three bus

balanced distribution system that includes OLTC, three phase electrical load, three phase

capacitor bank, and PV system. Three phase load contains 500 kW active power and 200

kVAR reactive power. The numbers are selected such that a voltage drop exists at the end

of the line. The objective function is minimizing the total line losses and the decision

variables are the OLTC tap position, turning on and off state of the capacitor bank, and

injecting or absorbing reactive power amount of the PV. GA optimizes the tap position,

capacitor on and off state, and reactive power amount that needs to be injected or absorb

by PV. The PV reactive power is controlled by PID controller. Equations 8 through 11

show the objective function in this case of study. The details of the Line 1 power loss

calculation in terms of OLTC tap position is provided in equation 20. OLTC is controlled

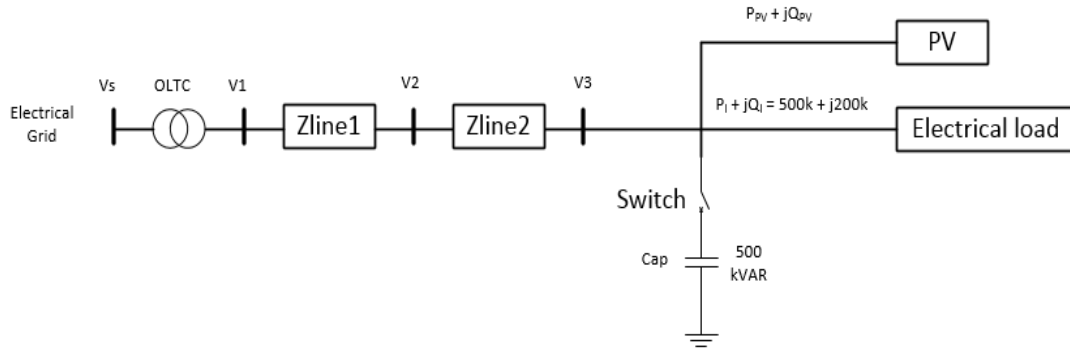by controlling the N in the objective (fitness) function.

Figure 18. Case 1 test system

$$P_{loss} = \text{Min} \sum (P_{line1} + P_{line2}) \tag{19}$$

where

P_{line1} is the power loss between buses 1 and 2

P_{line2} is the power loss between bus 2 and 3.

$$P_{line1} = \frac{\left[V1 \times \dfrac{1}{1 + N\Delta V} \times \dfrac{Vnom2}{Vnom1} - V_2\right]^2 \times R_1}{|Z_{Line}|^2} \tag{20}$$

Equation 21 calculates the power loss P_{line2} at Line 2 The current is written in terms of active and reactive power and substituted in line loss calculation.

$$P_{line2} = I^2 \times R = \left(\frac{S}{V}\right)^2 \times R = \left(\frac{\sqrt{P^2 + Q^2}}{V}\right)^2 \times R = \frac{P_3^2 + Q_3^2}{V^2} \times R \tag{21}$$

The final fitness function becomes:

$$P_{loss} = \text{Min} \sum \frac{\left[V1 \times \frac{1}{1 + N\Delta V} \times \frac{Vnom2}{Vnom1} - V_2\right]^2 \times R_1}{|Z_{Line}|^2} + \frac{P^2 + [Q_L - x_c Q_{Cap} + Q_{PV}]^2 \times R}{V_2^2} \qquad (22)$$

where

V$_1$ the grid voltage.

N the tap position in the OLTC.

ΔV is the voltage difference between two tap positions in the OLTC

V$_{nom1}$ is the nominal voltage in the primary side of the OLTC

V$_{nom2}$ is the nominal voltage in the secondary side of the OLTC

V$_2$ is the voltage at bus 2

R is the transmission line resistance

P is the power load at bus 2

Q$_L$ is the load reactive power

Q$_{Cap}$ is the capacitor reactive power

Q$_{PV}$ is the reactive power generated by the PV.

Z is the transmission impedance

The system constraints are:

-8 < Tap Position < 8

$0 < x_c < 1$ (Capacitor on/off state)

-100 kVAR < Q$_{PV}$ < 100 kVAR

$0.95 \text{ pu} < V_3 < 1.05 \text{ pu}$

The decision variable of the system are, OLTC tap position, capacitor state, Kp,Ki, and Kd values.

The circuit model is developed in Simulink as shown in Figure 19. The simulation is part of the optimization process and controlled by a Matlab m-file. The optimization uses parallel pool functionality of Matlab that utilizes 30 cores of the computer to reduce the time for the iterations.
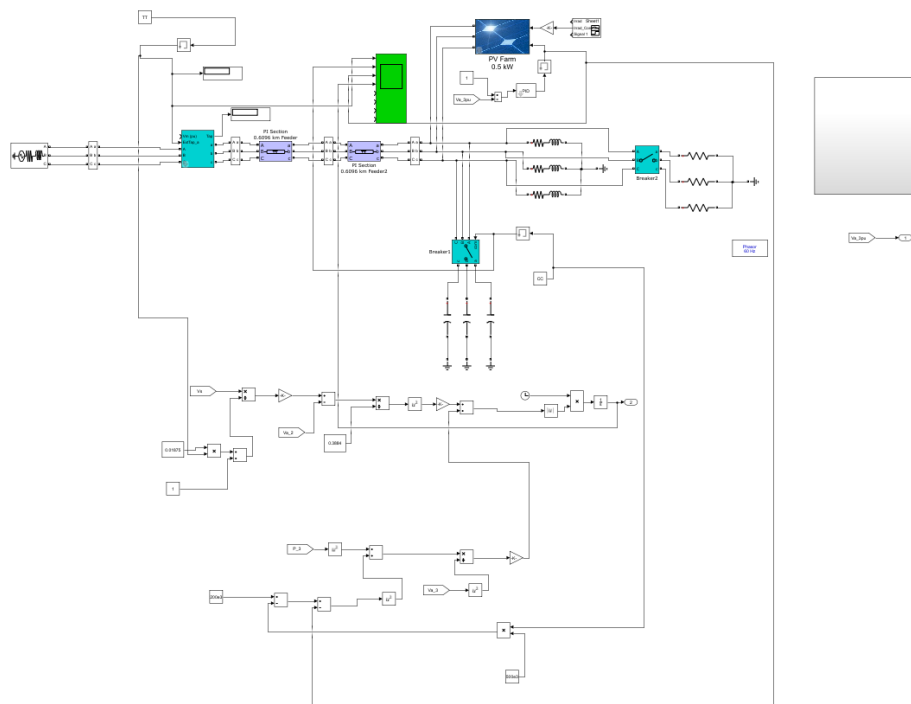

Figure 19. Circuit simulation in Simulink

One of the constraints is to keep the voltage at the PCC where the PV and capacitor is connected within 0.95 p.u and 1.05 pu. When V_3 is within the range the rest of the system voltage will be in acceptable range since Bus 3 is the end point in the line. The optimization takes the V_3 as constrain during the optimization. Table 1 shows the optimization results after 172 iterations.

Table 1

Optimization parameters (case 1)

OLTC Tap position	Capacitor state (on=1, off=0)	Kp	Ki	Kd
1	0	1,491	636	2,175

This optimization results for the decision variables are plugged into the simulation and then run. Results show that the simulation can run successfully and the V_3 voltage stays at 1 pu as shown in Figure 20. Bus 3 voltage reaches to 1 pu value in a very short period of time which shows that the PID controller responses to the changes immediately. Since the load power is constant through the simulation, once the V_3 reaches to 1 pu, it stays there until the end of the simulation.
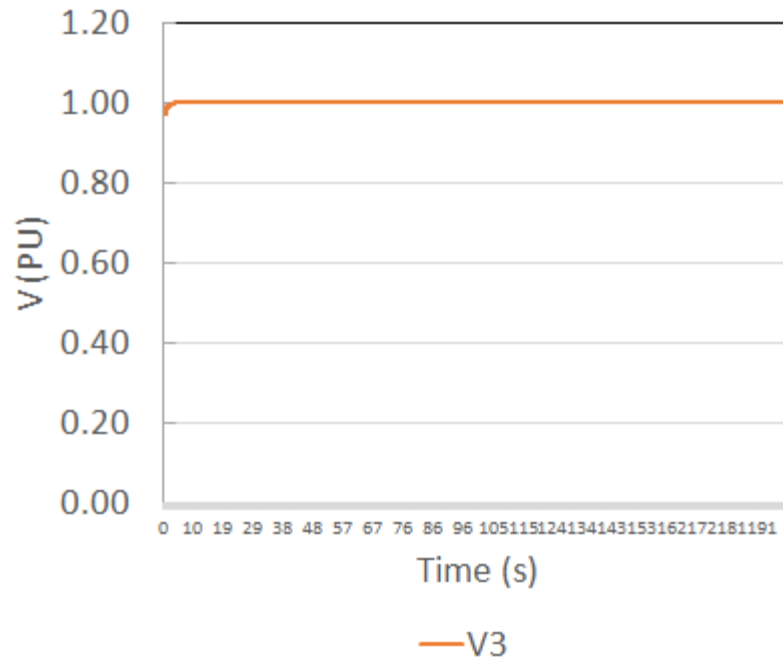
Figure 20. V$_3$ voltage

<div align="center">Case 2</div>

The algorithm was implemented for IEEE 13-buses system. The control system is a three phase control system which means the tap positions for the three phases change simultaneously and the reactive power absorbed or injected by the PV system is the same for all phases. Positive sequence voltage is used to keep the PCC bus voltage at 1 pu reference value. The positive sequence, which considers mutual impedance, for phase A for each bus is used to make the decision. The purpose of using positive sequence in this case study is to observe the difference between the single phase control and three phase control in the next case study. IEEE 13-buses system is an unbalanced system which means having a three phase control will not improve the individual bus voltages at the

same time. The results show that the control algorithm can optimize the system and find

the parameters to reduce the losses, however, the each phase bus voltages are different

from each other as a result of unbalanced system. As it can be seen from Table 2,

although the phase A positive sequence voltage is 1 p.u., the individual bus voltages

varies within a wide range.

As seen in Figure 21, PV injected the reactive power needed to maintain the

voltage within the acceptable range. The voltage at bus 675 is 1 pu.
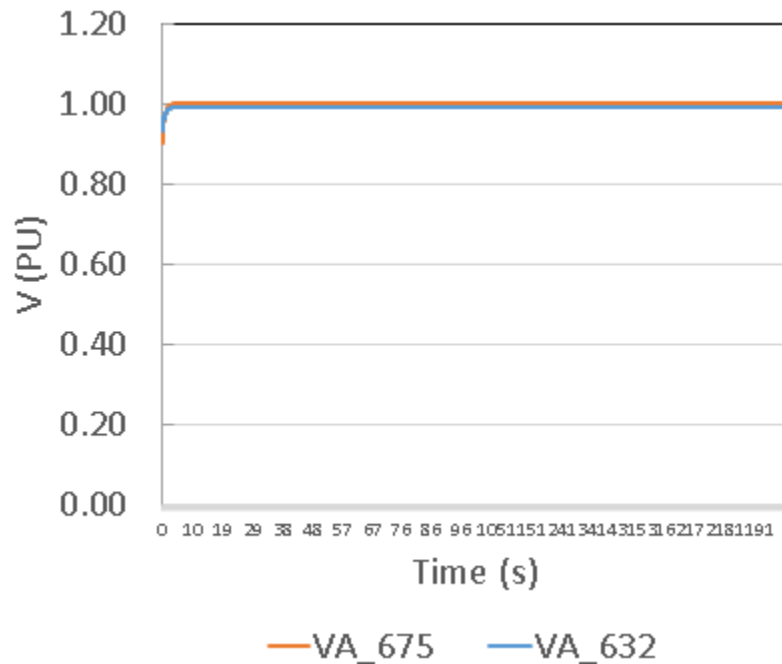
Figure 21. Voltages at buses 632 & 675 (Case 2)

As seen in Figure 22, PV injected 1.6 MVAR to maintain the voltage at 1 pu at bus 675. Changing the tap position in the OLTC was not needed as the reactive power from the PV was enough to maintain the voltage within the acceptable range.

Figure 22. Reactive power injected from PV system (Case 2)

The results from the optimization process are as follows:

Table 2

Optimization Parameters (case 2)

OLTC Tap position	Capacitor state (on=1, off=0)	Kp	Ki	Kd
0	1	3,823	7,687	472

Positive voltage for all phases in each bus can be seen in Table 3.

Table 3

Buses voltage (Case 2)

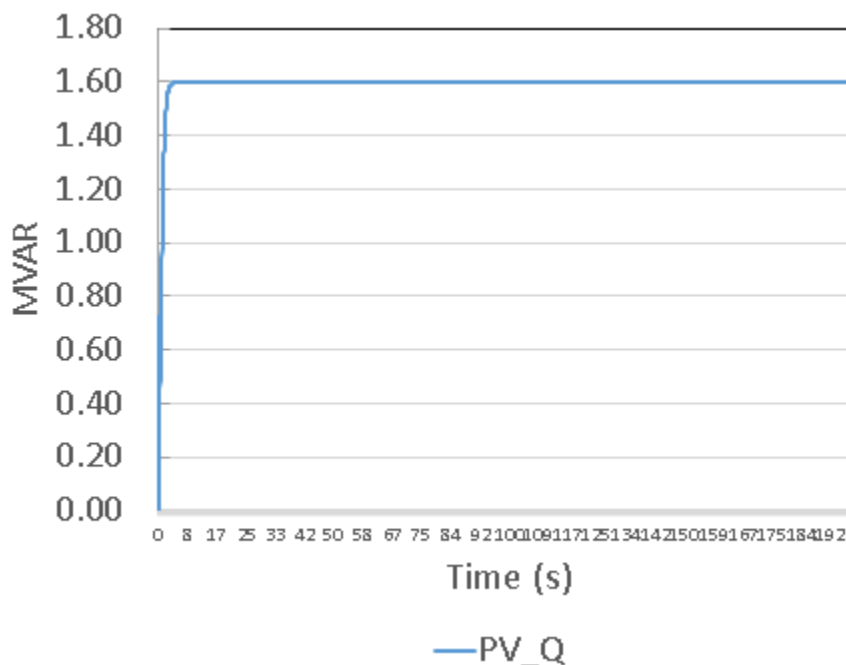| Bus	Voltage (pu)	Bus	Voltage (pu)
Va_633	0.9072	Va_684	0.9947
Vb_633	1.222	Vb_684	0.9947
Vc_633	0.8729	Vc_684	0.9947
Va_671	0.9165	Va_632A1	0.9103
Vb_671	1.251	Vb_632A1	1.226
Vc_671	0.8617	Vc_632A1	0.8742
Va_634	0.8861	Va_632A2	0.9103
Vb_634	1.2	Vb_632A2	1.226
Vc_634	0.8568	Vc_632A2	0.8742
Va_692	0.9165	Va_632A3	0.9103
Vb_692	1.251	Vb_632A3	1.226
Vc_692	0.8617	Vc_632A3	0.8742
Va_680	0.9165	Va_684A1	0.9165
Vb_680	1.251	Vb_684A1	1.251
Vc_680	0.8617	Vc_684A1	0.8617

The results show that the proposed method successfully defines the decision variables based on positive sequence values, however, the three phase control algorithm does not have the capability to improve the balance in the system since the PV injection and absorption are equal in each phase. In this case, the algorithm cannot maintain the voltages in all busses within the acceptable range. The results show that three single phase controlled system is needed.

<div align="center">Case 3</div>

In addition to IEEE 13-buses, PV, and capacitor bank that were added to 675 in case 2, a single phase controlled system is implemented for the PV, capacitor banks, and OLTC. The fitness function was modified to calculate the losses for the whole system and the numbers of decision variables are 12 due to single phase components. The controller is changed to PI and the load connected to bus 675 controlled by a circuit breaker which is closed at 100 second and open again at 150 second of the simulation to observe the PI response.

The algorithm is designed to maintain all the phase voltages of buses 632 & 675 within 0.95 and 1.05 pu. As seen in Figure 23, GA maintains the voltage for phase A at buses 632 & 675 within the acceptable range. There are some oscillations at second 100 and second 150 when the switch at bus 675 closes and opens respectively. Although there are oscillations at second 100 and second 150, the voltages in all busses are maintained within the acceptable range.
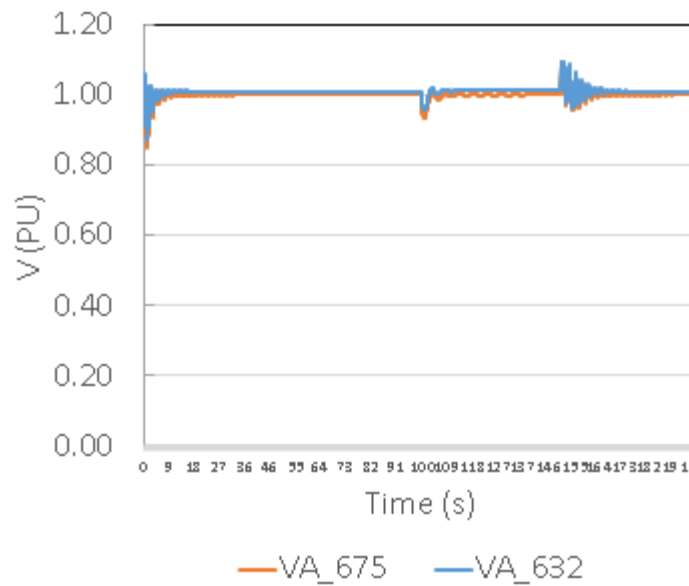
Figure 23. Voltages at buses 632 & 675 (Case 3)

As seen in Figure 24, PV system has to inject more reactive power between second 100 and 150 because a three phase load is added to bus 675. The increase in the reactive power is needed to maintain the voltage at bus 675 within the acceptable range.
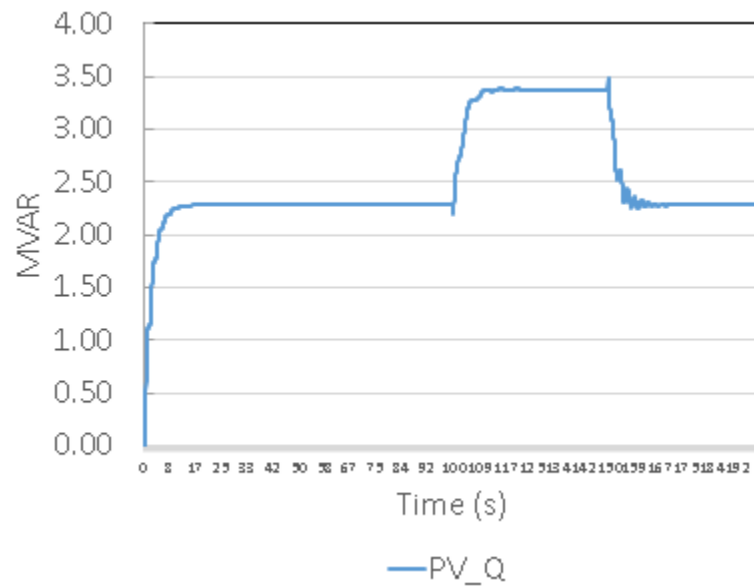
Figure 24. Reactive power injected from PV system (Case 3)

Table 4 shows the three phase voltage for all the buses. GA maintains the voltage for all the buses within the acceptable range. Single phase controlled system improve the balance in the system as it injects and absorbs reactive power based on the need of each phase.

Table 4

Buses voltage (Case 3)

Bus	Voltage (pu)	Bus	Voltage (pu)
Va_633	1.007	Va_684	0.9992
Vb_633	0.975	Vb_684	0.9952
Vc_633	0.9837	Vc_684	0.9917
Va_671	1.001	Va_632A1	1.011
Vb_671	0.9952	Vb_632A1	0.9768
Vc_671	0.9931	Vc_632A1	0.986
Va_634	0.9838	Va_632A2	1.011
Vb_634	0.957	Vb_632A2	0.9768
Vc_634	0.9655	Vc_632A2	0.986
Va_692	1.001	Va_632A3	1.011
Vb_692	0.9952	Vb_632A3	0.9768
Vc_692	0.9931	Vc_632A3	0.980
Va_680	1.001	Va_684A1	1.001
Vb_680	0.9952	Vb_684A1	0.9952
Vc_680	0.9931	Vc_684A1	0.9931

The decision variables found by the optimization are given below. OLTC tap position does not change. All the capacitors have to be disconnected except the capacitor for phase C.

Table 5

The optimized parameters (Case 3)

Decision Variable	Value
OLTC-A	0
OLTC-B	0
OLTC-C	0
Capacitor-A	0
Capacitor-B	0
Capacitor-C	1
Kp-A	-1,944
Kp-B	-4,410
Kp-C	-2,280
Ki-A	-2,046
Ki-B	-6,549
Ki-C	-3,058

Case 4

In addition to case 3, a dynamic load is added to bus 680 and variable irradiance to the PV system. As seen in Figure 25, the algorithm can optimize the system to maintain the voltage within the acceptable range. As in case 3, there are some oscillations at the very beginning and at 100 seconds and 150 second due to switching on and off the load at bus 675.

Figure 25. Voltages at buses 632 & 675 (Case 4)
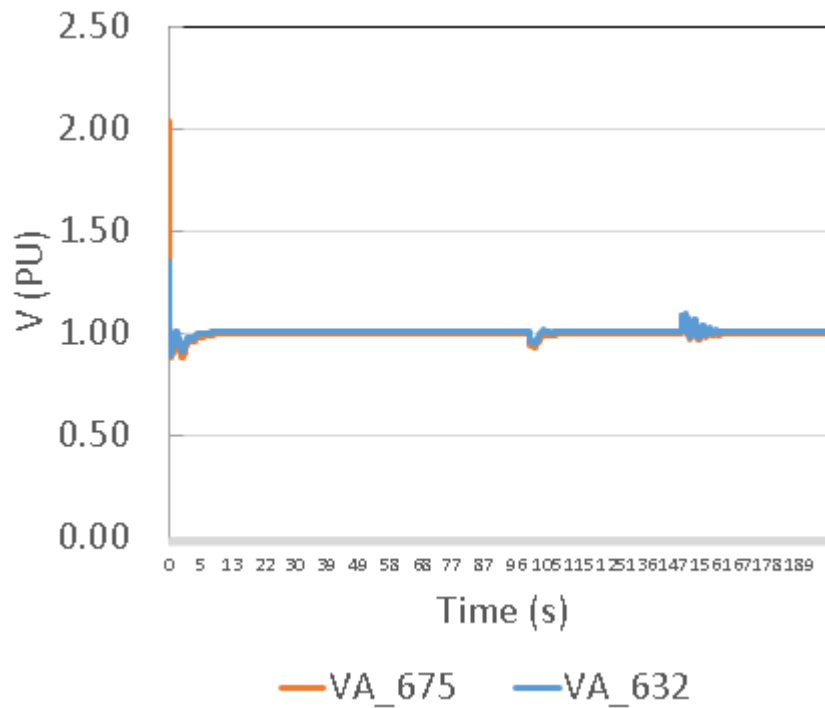
As seen in Figure 26, PV has to inject more reactive power between 100 second and 150 second because of adding the load at 675. The reactive power injected to the

system is following the same pattern as in case 3 with some changes due to the dynamic
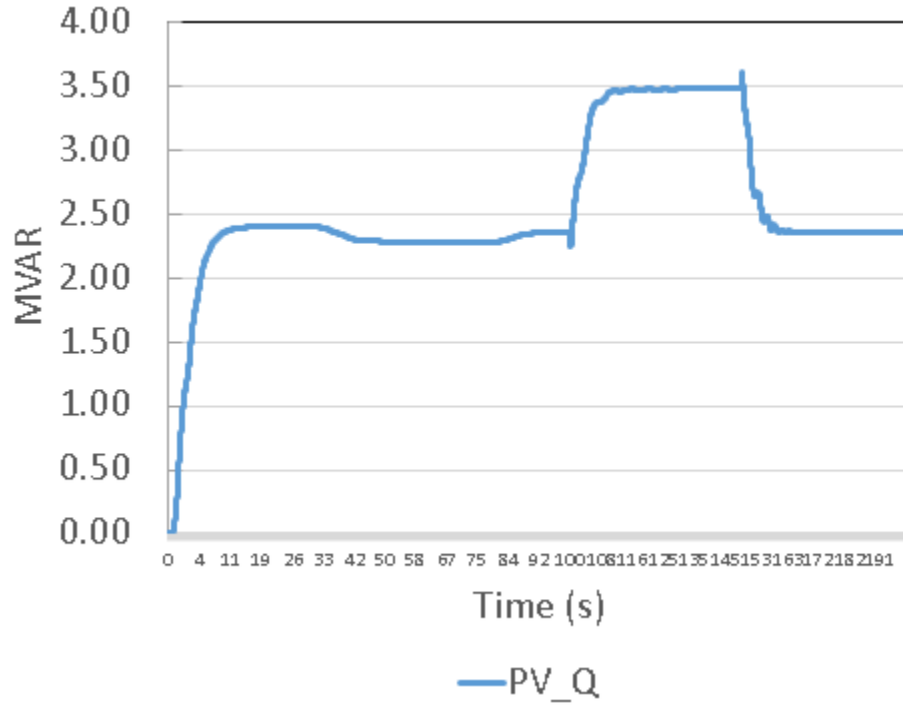
load.

Figure 26. Reactive power injected from PV system (Case 4)

The voltage in each phase can be seen in Table 6.

Table 6

Buses voltage (Case 4)

Bus	Voltage (pu)	Bus	Voltage (pu)
Va_633	1.008	Va_684	0.9994
Vb_633	0.9752	Vb_684	0.9954
Vc_633	0.9836	Vc_684	0.9919
Va_671	1.001	Va_632A1	1.011
Vb_671	0.9953	Vb_632A1	0.9769
Vc_671	0.9932	Vc_632A1	0.9859
Va_634	0.984	Va_632A2	1.011
Vb_634	0.9571	Vb_632A2	0.9769
Vc_634	0.9654	Vc_632A2	0.9859
Va_692	1.001	Va_632A3	1.011
Vb_692	0.9953	Vb_632A3	0.9769
Vc_692	0.9932	Vc_632A3	0.9859
Va_680	1.001	Va_684A1	1.001
Vb_680	0.9953	Vb_684A1	0.9953
Vc_680	0.9932	Vc_684A1	0.9932

<u>Summary</u>

The proposed algorithm was tested and verified in case 1 in a small scale distribution system. In case 2, the same algorithm was implemented in a bigger scale system. The system was designed based on the positive sequence for each phase which is not the best method to control the voltage in un-balanced distribution system. In case 3, the system was designed as a three single phase controlled system. Case 3 showed the ability to improve the balance in the distribution system by using three single phase controlled system. The number of tap position changes for the OLTC is reduced compared to the base case in Figure 13. Case 4 showed how the algorithm can handle a dynamic load.

The results show the ability of GA to optimize electrical distribution system. It also shows that the algorithm can optimize OLTC, and PV system with the ability to meet the constraints in each case.

CHAPTER 5

CONCLUSION AND FUTURE RECOMMENDATIONS

PV system has been growing rapidly in the last decade. There are a lot of sectors using PV system including commercial and residential applications. Chapter 1 introduced the importance of the PV systems and how they grow rapidly. It also provided some background about PV installation and the challenges facing it. Chapter 2 introduced literature review about voltage regulation using PV, and optimization in the electrical distribution systems. This chapter explored the contributions of this dissertation to the integration of PV systems connected to the grid. Chapter 3 discussed the methodology of the dissertation. It provided more information about the equations used and the theory behind them. Chapter 4 produced 4 cases of study for the proposed algorithm. It provided the results and what can be observed from them.

Conclusion

The dissertation presented a voltage control of unbalanced distribution system using GA. PV system was added to IEEE 13 bus system and simulated using Matlab and Simuink. This section answers the research questions.

How can coordinated control improve the voltage profile of an unbalanced distribution system?

As seen in test cases, the coordinated control system can maintain the voltages within the acceptable range. The coordinated control system solves the technical problems associated with the increase of PV installation such as overvoltage and voltage unbalance.

Would PV reduce the OLTC operation?

OLTC tap changing operation is reduced as the PV system injects the reactive power needed to maintain the voltage within the acceptable range. Reduced operation increases the life time for the OLTC, and reduces the maintenance cost as the number of operations is less.

How can OLTC and PV system control unbalanced distribution system voltage?

Three phase positive sequence control algorithm reduces the power losses, but keeps the distribution system still unbalanced. It limits the ability to reduce the power losses because it cannot regulate each phase individually. To improve the balance in the system, three single phase control system is needed. Three single phase control algorithm for OLTC and PV system has the ability to regulate the voltage more than the three phase positive sequence control system. Three single phase control algorithm changes the system to a balanced system in terms of system voltage. It has the ability to maintain the voltage within the acceptable range even if there is a dynamic load.

How can GA optimize the distribution system to reduce the electrical losses?

GA has the ability to optimize the distribution system operation. It can reduce the tap position changes for the OLTC. It also finds the optimum PI controller settings for PV's reactive power control to reduce the power losses in the distribution system.

Future Recommendation

The algorithm was implemented and verified using IEEE 13 bus, but still there are a lot of opportunities to extend the scope of the dissertation. This section provides some ideas and recommendations for future works.

One of the limitations of this dissertation is the price of the generated electricity from PV or from different plants in the electrical grid. The price could be a parameter in the fitness equation. The optimization algorithm will make the decision to inject or absorb reactive power or change the tap position for the OLTC based on the price. Also, this algorithm was implemented only in IEEE 13 bus system. Another recommendation is to implement it using a larger scale electrical distribution system. To implement it, a higher processor PC or simulator needs to be used as larger system will need more iterations to find the parameters.

Using battery storage could be another recommendation to expand the scope of the dissertation. A battery storage can be added to each PV. The algorithm can make the decision to charge the battery based on the output power from the PV and the electrical demand.

REFERENCES

Aggarwal, R. P., & Yishengpan. (1989). Minimization of Real Power Losses Using Reactive Power Control. *Electric Power Systems Research, 17*, 153-157.

Alam, M. J., Muttaqi, K. M., Sutanto, D., Elder, L., & Baitch, A. (2012). *Performance analysis of distribution networks under high penetration of solar PV.* Wollongong, Australia: Univerity of Wollongong.

Albuquerque, F., Moraes, A., Guimaraes, G., Sanhueza, S., & Vaz, A. (2010). Photovoltaic solar system connected to the electric power grid operating as active power generator and reactive power compensator. *Solar Energy*, 1310-1317.

Ali, I., & Kucuksari, S. (2016). Voltage regulation of unbalanced distribution network with distributed generators. *2016 North American Power Symposium (NAPS).* Denver, CO: IEEE.

Calderaro, V., Conio, G., Galdi, V., & Piccolo, A. (2012). Reactive power control for improving voltage profiles: A comparison between two decentralized approaches. *Electric Power Systems Research*, 247-254.

Chen, P., & Salih, N. (2015). On Coordinated Control of OLTC and Reactive Power Compensation for Voltage Regulation in Distribution Systems With Wind Power. *IEEE Transactions on Power Systems*, 1-10.

Chen, Y., & Xue, D. (2014). *System Simulation Techniques with Matlab and Simulink.* John Wiley & Sons.

Danfoss Group Global. (2013). *Voltage control in low voltage networks by Photovoltaic Inverters.* Nordborg, Denmark: Danfoss.

Dohnal, D. D. (2013). *On-Load Tap-Changers For Power Transformers.* Regensburg, Germany: Maschinenfabrik Reinhausen GmbH.

Hamzaoui, I., Bouchafaa, F., & Hadjammar, A. (2011). Inverstigation of the behavior of a three phase grid-connected photovoltaic system to control active and reactive power with DPC. *Energy Procedia*, 493-502.

Haque, M. M., & Wolfs, P. (2016). A review of high PV penetrations in LV distrinution networks: Present status, impacts and mitigation measures. *Renewable and Sustainable Energy Reviews*, 1195-1208.

Harnett, S. (2016). *Optimization Methods for Power Grid Reliability.* New York City, NY: Columbia University.

Hassaine, L., Olias, E., Quintero, J., & Haddadi, M. (2009). Digital power factor control and reactive power regulation for grid-connected photovoltaic inverter. *Elsevier*(34), 315-321.

Haupt, R., & Haupt, S. (2004). *Practical Genetic Algorithms.* (Second, Ed.) Hoboken, NJ: A John Wiley & Sons, INC., Publication.

Hu, J., Marinelli, M., Coppo, M., & Zecchino, A. (2016). Coordinated voltage control of a decoupled three-phase on-load tapchanger transformer and photovoltaic inverters for managingunbalanced networks. *ELSEVIER*, 264-274.

International Energy Agency. (2017, December). *Renewavles 2017*. Retrieved April 13, 2018, from https://www.iea.org/publications/renewables2017/

Jayakrishan, B., Kothari, P., Nedumgatt, J., Umashankar, S., & Vijayakumar, D. (2011). Perturb and Observe MPPT Algorithm for Solar PV Systems-Modeling and Simulation. *India Conference (INDICON)* (pp. 1-6). Hyderabad, India: IEEE.

Jayasekara, N., Wolfs, P., & Masoum, M. A. (2014). An optimal management strategy for distributed storages in distribution networks with high penetrations of PV. *ELSEVIER*, 147-157.

Jung, J., Onen, A., Arghandeh, R., & Broadwater, R. (2014). Coordinated control of automated devices and photovoltaic generators for voltage rise mitigation in power distribution circuits. *Renewable Energy*, 532-540.

Kjaer, S. B., Pederson, J. K., & Blaabjerg, F. (2005, September/October). A Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules. *IEEE Transactions on Industry Applications, 41*(5), 1292-1306.

Kolenc, M., Papic, I., & Blazic, B. (2012). Minimization of Losses in Smart Grids Using Coordinated Voltage Control. *Energies*, 3768-3783.

MathWorks. (2017). *MATLAB Help.* Natick, MA: Mathworks.

National Grid Electricity Transmission. (2010). *The Grid Code.* Warwick, United Kingdom: National Grid Electricity Transmission.

Nazir, R., Kanada, K., Syafii, & Coveria, P. (2015). Optimization active and reactive power flow for PV connect to grid system using Newton Raphson Method. *Energy Procedia*, 77-86.

Overstraeton, R. J., & Mertens, R. P. (1986). *Physics, technology and use of photovoltaic.* Bristol, England: Adam Hilger.

Patriksson, M., Andreasson, N., & Evgrafov, A. (2017). *An Introduction to Continuous optimization: Foundations and Fundamental Algorithms.* (3rd, ed.) New York, NJ: Dover Publications Inc.

Perera, B., Ciufo, P., & Perera, S. (2016). Advanced point of common coupling voltage controllers for grid-connected solar photovoltaic (PV) systems. *Renewable Energy*, 1037-1044.

Rafi, F., Hossain, M., & Lu, J. (2016). Hierarchical controls selection based on PV penetrations for voltage rise mitigation in a LV distribution network. *Electrical Power and Energy Systems*, 123-139.

Ramos, S. C. (2014). *Optimization of the operation of a Distribution Network with Distributed Generation using Genetic Algorithm.* Barcelona: Universitat Politecnica de Catalunya.

Riffonneau, Y., Bacha, S., Barruel, F., & Ploix, S. (2011). Optimal Power Flow Management for Grid Connected PV Systems With Batteries. *IEEE Transactions on Sustainable Energy, 2*(3), 309-320.

Turitsyn, K., Sulc, P., Bachaus, S., & Chertkov, M. (2011). Options for Control of Reactive Power by Distributed Photovoltaic Generators. *IEEE, 99*(6), 1063-1073.

US Energy Information Administration. (2017, April 27). *United States Electricity Profile 2015*. Retrieved from US Energy Information Administration: https://www.eia.gov/

Viawan, F. A. (2008). *Voltage Control and Voltage Stability of Power Distribution Systems in the Presence of Distributed Generation.* Goteborg, Sweden: Chalmers University of Technology.

Yang, F., Yang, L., & Ma, X. (2014). An advanced control strategy of PV system for low-voltage ride-through capability enhancement. *Solar Energy*, 24-35.

APPENDIX

NAPS 2016

Voltage Regulation of Unbalanced Distribution Network with Distributed Generators

Islam Ali
Department of Technology
University of Northern Iowa
Cedar Falls, USA
hassani@uni.edu

Sadik Kucuksari
Department of Technology
University of Northern Iowa
Cedar Falls, USA
sadik.kucuksari@uni.edu

Abstract—**Distribution networks are not perfectly balanced all time due to the nature of dynamic loads in the system. Photovoltaic (PV) systems started to be integrated into these distribution networks as distributed generators (DG) through inverters. In addition, wind turbines also started to be integrated but not as distributed as PVs. Both DGs have a fluctuating power outputs due to the intermittent resources that can affect the voltage profile of the system and can also increase the OLTC operation which has limitation on precise voltage regulations as well as on response time to the voltage changes. Inverters can reduce these effects and regulate the voltage by injecting reactive power. This paper presents a study on the distributed PV voltage control of an unbalanced distribution network that includes OLTC and wind turbine generation at the substation. Single phase PV and OLTC voltage control is proposed. In addition, the wind turbine impact on distribution network is investigated. IEEE 13 bus distribution network is simulated in Matlab Simulink and feeder bus voltages are monitored when OLTC, PV, and wind turbine provide voltage regulation. Results show that voltage profile of point of common coupling stays within the limits with the help of PV single phase voltage regulation. The OLTC operation depends on the PV voltage control and injected power amount. Results also show that the OLTC operation is reduced with the PV voltage control and wind turbine has impact on the voltage profile.**

Keywords— *Photovoltaic systems, reactive power, voltage profile, OLTC, wind turbine, unbalanced distribution network.*

I. INTRODUCTION

THE vertical paradigm of the electrical distribution system has been changed over the last decade. In the traditional vertical paradigm, the electrical power flow has only one direction, from generation to customers. This vertically integrated power grid has to provide continues power to the increasing electrical demand [1]. The United States Energy Information Administration expects that the electrical demand in 2035 will be increased by 50% compared to the demand in 2008 since the population, technology, and industry grows [2]. Changing the old paradigm from unidirectional to bidirectional power flow by adding distributed generators will increase the efficiency, performance, and the voltage profile in the electrical grid.

The main change in the power grid nowadays is the addition of distributed generators (DG) which can provide power from end users to the grid. Photovoltaic (PV) systems are one of the fast growing DG industry and their integration with the power grid has increased significantly. In 2005 alone, the globally installed PV was 5.4 GW. In 2012, the overall installed PV exceeded 100 GW worldwide. It is expected that this number will increase in the next couple of years [3]. As the number of PV systems increases, it brings some concerns for the power system operation. One of the concerns is on the voltage profile of the system especially during the light load scenarios [4]. Based on a survey that Danish distribution network operators conducted, the urgent issues were overvoltage, voltage unbalance, and overloading caused by the PV systems. There are some approaches to overcome these problems such as charging and discharging batteries other than injecting PV generated power back to the grid. However, this solution brings other challenges for the bidirectional power system [4]. Allowing DGs to inject and absorb electrical power to keep the point of common coupling (PCC) voltage with in the desired levels is another solution. The German standard VDE 4105 mentions that all the DGs connected to a low voltage system shall apply power factor adjustment to support the voltage regulation. The power factor adjustment varies based on the electrical source [5]. IEEE 1547 Standard for interconnecting DGs has an amendment on the voltage regulation by controlling DG active and reactive powers.

While DGs have control on the voltage, other voltage regulators in the network has to continue to operate without any problem. The existing power grid voltage regulators such as On Load Tap Changer (OLTC), synchronous generators, and capacitors are used to maintain the voltage within desired level, e.g. ±5%. OLTC uses the tap changers that moves the tap position on windings mechanically to keep the voltage within certain level. The number of taps changes according to the OLTC design and may limit the voltage control. In addition, the mechanical operation causes certain delay on voltage regulation. However, PV voltage support plays a significant role on the voltage regulation by having fast response time and more precise voltage regulations [6].

Recent studies [7-9] present the importance of voltage regulation in a distribution system that includes OLTC. Several control strategies are presented to keep the voltage

within the limits and to increase the PV power integration amount. Real network data is used for the Monte Carlo-based simulations. Researchers in [10] present a study showing the PV participation on voltage control. A distribution network is simulated using real time simulator and future scenarios on OLTC and PV control on voltage is presented. Study shows that coordinated control is needed to minimize the OLTC operation. Another study [11] presents a control strategy using swam optimization and dynamic programming for voltage control of distribution network that includes OLTC and PV.

All of these studies show that the OLTC operation depends on the PV power injection amount, specifically reactive power amount since it helps to control the voltage at the PCC. However, unbalanced distribution system is not well investigated. In addition, the impact of wind turbine on distribution system needs to be studied as well. This paper presents a simulation study that investigates the OLTC operation when the PV regulates voltage at the point of coupling for different scenarios. Both OLTC and PV voltage control is proposed as each phase control. The objective is to analyze the voltage profile of the busses on distribution feeders when reactive power is injected by the PV to regulate the PCC voltage of each phase. This paper presents a future case application of PV inverters since single phase PV voltage control is not a common practice nowadays but has the capacity. This study also shows the OLTC, PV, and wind turbine operations on voltage control using phasor simulations in Matlab Simulink. IEEE 13 bus distribution feeder is presented and simulated with two distributed PVs and one wind turbine connected to the substation. This paper is organized as follows. Section II presents the description of the test feeder and different cases. Simulation results are presented and discussed in Section III and conclusion is given in Section IV.

II. DESCRIPTION OF THE DISTRIBUTION NETWORK AND CASE STUDIES

In this study, IEEE 13 bus distribution system feeder [12] is simulated in Matlab Simulink. The single line diagram of the test system is depicted in Fig. 1. System includes OLTC at the substation, several loads at different locations through several branches. Shunt capacitor is included in the system which provides voltage support after the circuit breaker between buses 671 and 692 closes and additional loads are connected. Loads in the system are connected as single, two, and three phases that causes the network to be unbalanced. 500 kW PV is added to bus 680 and 250 kW PV is added to bus 684. 1.5 MW DIFG wind turbine is added to bus 632 which is the secondary side of the OLTC transformer at substation. The total system power demand is 3.5 MW. Matlab provided OLTC model is used in this study. The model is modified according to the test system transformer specifications. In addition, the model is modified to control each phase individually. The single phase bus voltages at bus 632 are

monitored and used to regulate each phase voltages at 1 pu. Initial tap positions for each phase is zero. Initially the capacitor bank and loads are disconnected through the circuit breaker which is closed later in the simulations to monitor the OLTC and other voltage controllers' operations and responses to the change in the load.
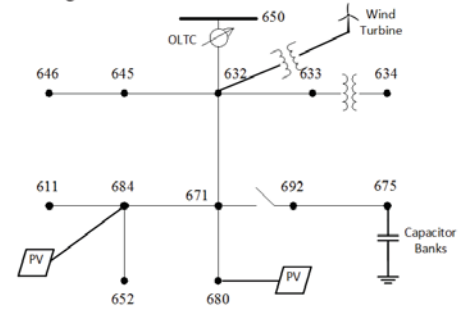

Fig. 1. Modified IEEE 13 bus [12] test system.

The phasor models of wind turbine and PV available in Matlab are used as the distributed generators. The PV model is modified such that it monitors each phase voltages and inject reactive power as needed to keep the PCC bus voltage at 1 pu. The model is a current source and does not include detailed inverter model, therefore, no detailed sinewave analysis achieved. Highly variable two minute field recorded irradiance data (increase slightly at t=30~40 s and decrease t=80~90 s.) for the month of August is used as an input. The reactive power capacity of the PVs can be adjusted for the case studies. It is assumed that the PV has fixed active power and variable reactive power outputs. The PV controllers continuously monitor the PCC bus voltages and compare it with the reference voltage value of 1 pu. PI controller is used to adjust the required reactive power. Wind turbine model is connected to the substation bus to represent single location integration and injects both active and reactive power. The following four case studies are performed using the test system:

Base Case: IEEE 13 bus distribution system without any DG addition is simulated and comparison between the modified OLTC and a transformer without regulation is performed.

Case 1: Two PV systems are installed at buses 680 and 684. Wind turbine is installed at bus 632. PV systems and wind turbine inject only active power.

Case 2: In addition to Case 1, PV systems and wind turbine inject reactive power to control the voltage PV systems control each phase voltage and wind controls only its PCC voltage.

Case 3: The reactive power amounts injected from the two PV systems are limited with 0.075 MVAR to monitor the OLTC and wind turbine operations.

III.   SIMULATION RESULTS

A. Base Case

The voltage profile in bus 632 and the OLTC tap positions for each phase are monitored and results are shown in Fig. 2. bus 632 voltage is monitored since it is the main bus that distributes the power to the rest of the system. The voltage regulation of the OLTC is disabled and the tap position is fixed at zero position. The voltage magnitude varies between 0.92 and 0.93 pu for each phase during the simulation time. At 60 secs, the circuit breaker is closed to add buses 692 and 675 in to the system. A change in the voltage magnitudes for each phase is determined due to the added buses. Results show that the bus voltage is over the %5 limits without any voltage regulation in the system and the system is unbalanced. The voltage drops at the other buses are also significant.
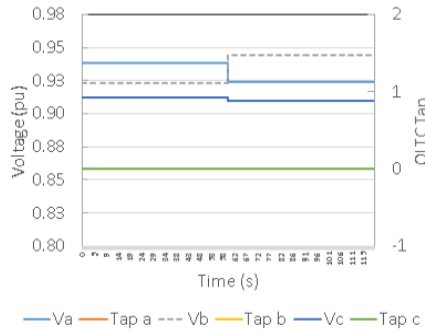
Fig. 2. Base without voltage regulation. (bus 632)

The regulation in OLTC is enabled to maintain the bus 632 voltage at 1 pu. Fig. 3 shows the each bus voltages and OLTC tap positions. Each tap positions are changed independently to maintain the voltages which verifies the modified OLTC operation for each phase voltage control. However, it is seen that the voltages are not at perfect 1 pu due to the OLTC dead-band limitation. OLTC changes its tap positions when there is a 0.03 pu voltage difference exists. The monitoring and operation interval is 3 sec which is also another limitation. The voltage peaks in the figure at the tap changing moments are due to the model limitations which can be disregarded according to the model description. After the circuit breaker operates at 60 sec the OLTC responses to the change in the voltage and change its tap positions to keep the voltage as close as possible to 1 pu. The voltage magnitude varies between 0.99 and 1.01 p.u during this operation period. These results show that the modified OLTC model for single phase control operates successfully.

B. Case 1

In this case study, two PV systems and wind turbine are added to buses 680, 684, and 632 respectively. PV systems and wind turbine are allowed to inject active power only. As the injected power increases, the bus 632 voltages increases. The results depicted in Fig. 4 shows that OLTC has to change the tap position for all the phases as in the base case study. However, tap position for phase C does not need to be changed to position -3 at this time since the PV systems and wind turbine are injecting active power which reduce the voltage drops, as a result, the operation frequency of the OLTC. Although new loads are added at t=60 sec, there is no OLTC operation exists due to the DGs and capacitor banks additions.
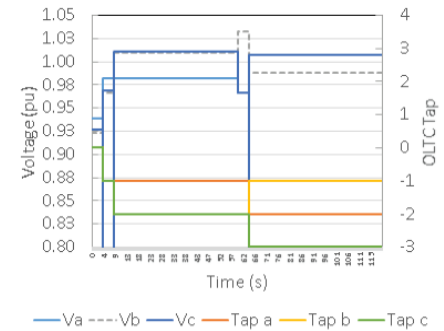

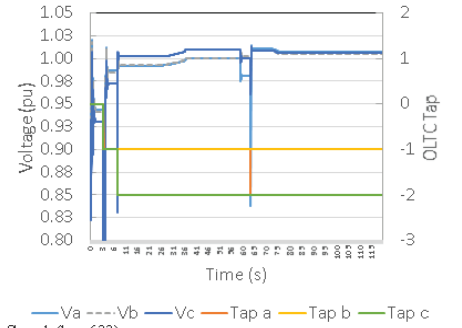Fig. 3. Base with voltage regulation. (bus 632)

Fig. 4. Case 1 (bus 632)

The system power flows are also presented in Figs. 5, 6, and 7 when DGs inject active power only. Fig. 5 show that grid injected reactive power varies around 1.38 MVAR and active power varies depends on the DGs injected active power. Grid reduces its active power at 22 sec as the wind turbine starts to inject more active power to support the electrical grid. PV at 684 generates 0.2 MW and PV at 680 generates 0.5 MW as set power amounts. The wind turbine injected power amounts are shown in Fig. 6. The injected active power changes as the wind speed changes and no reactive power is injected as desired. The PV injected power can be seen in Fig. 7. The generated active power reaches the maximum value between 30 and 80 sec when the irradiance reaches the maximum value. The short term oscillations at t=0 and switching moments are due to the model limitations that does not have significant impact on the operations.

The PV connected bus voltages are also monitored to observe the PV active power impact on voltage. Since the PV does not control the bus voltage, each bus voltages are not at 1 pu and changes as the injected active power changes. No reactive power is injected as seen in the figure. All the phase voltages are around 0.97 pu except phase C in bus 684 which is 1.01 pu. Although the bus 632 voltages are around 1 pu, the bus 680 and 684 voltages (Fig. 8) are less than 1 pu due to the voltage drop across the feeders. The only way to control the voltages in buses 680 and 684 in this case is through the OLTC control at bus 632.
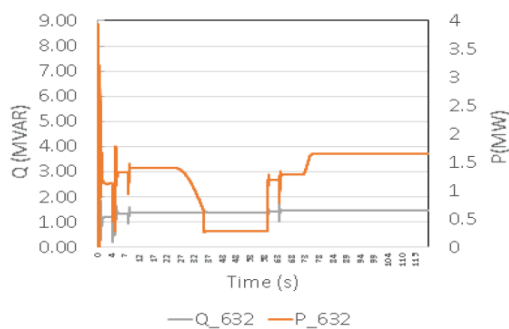
Fig.. 5. Grid active and reactive power at bus 632
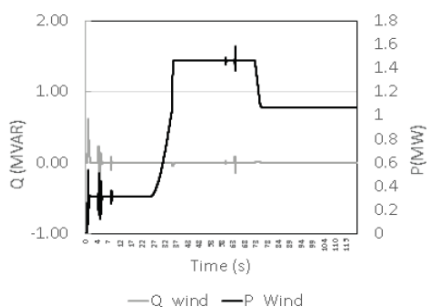
Fig. 6. Wind turbine active and reactive power.
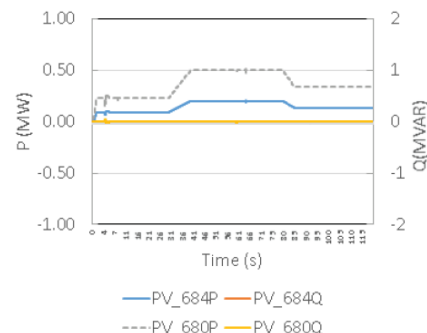
Fig. 7. PV 684 and PV 680 active and reactive power.

C. Case 2

In this case study, PV systems and wind turbine are allowed to inject reactive power to support the distribution system voltage. Fig. 9 shows single phase OLTC and PV control schematic. The voltage is controlled by injecting or absorbing reactive power. The measured voltage is compared with the voltage reference that can be adjusted according to the needs. The error from the comparison is used as an input to the PI controller. The output from the PI controller is the reactive power amount to be injected or absorbed from the PV.
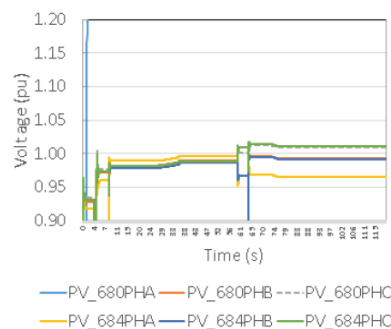

Fig. 8. Case 1 bus 680 and 684 voltages

As seen in Fig 10, the OLTC tap position for each phase does not change. The voltage in the distribution system is supported by PV systems and wind turbine. According to an international survey, most of the failures in the OLTC exist during the tap position switching since the load current is not interrupted at this moment. Therefore, the number of tap changing should be as minimum as possible [13]. The bus 632 voltage for each phase varies between 1.01 and 0.98 pu (dead band limit maintained) when voltage control exists.
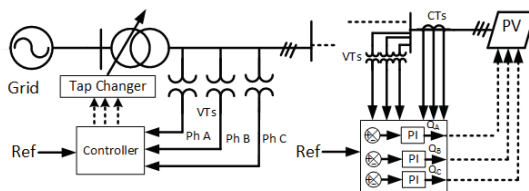

Fig. 9 Single phase PV control.

PV systems and wind turbine reactive power injection is monitored and presented in Figs. 11, 12, and 13. When DGs inject reactive power and control voltage, the grid injected reactive power is minimized and the exceeding reactive power is absorbed by the grid. At t=27 secs, the reactive power injected from the wind turbine starts to decrease, the electrical grid starts to compensate the difference and injects reactive power to the distribution system. After t=60 secs, the circuit breaker is closed to connect the capacitor banks to the system which injects reactive power. This power balance provides

successful voltage control at each phase. The results show that OLTC operation is minimized and provide voltage control at its own bus.
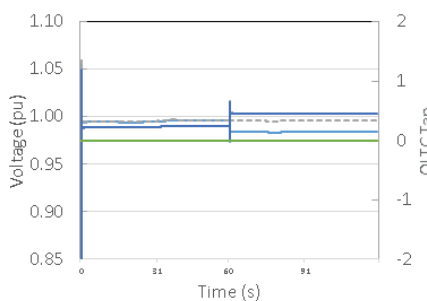

Fig. 10. Case 2 (bus 632)

Fig. 12 shows the wind turbine power outputs. The active power is still the same as in Case 2 but the reactive power is not zero. The amount of reactive power changes as need to control PCC voltage. The model provided voltage control is activated and successfully controls the voltage.
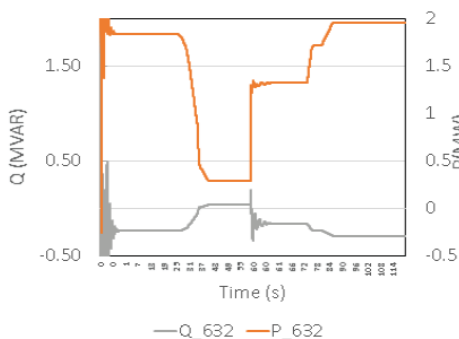

Fig. 11. Case 2 (bus 632)

Results help to understand the impact of wind turbines on distribution system. In this case study, the impact of wind turbine is observed for the substation connection and seen that it helps to supplement the system. The effect on voltage profile is positive since the wind turbine control mechanism operates successfully. Similar investigation for PV systems shows that single phase voltage control contributes to overall system operation. Fig. 14 shows the single phase controller results to maintain the voltage at 1 pu for all the phases in buses 684 and 680. Although there is a change in the irradiance, the voltage controller maintains the voltage at 1pu. There is some disturbance after 60 secs when buses 671 and 692 are connected to the distribution system. The PI controller adjusted the reactive power to maintain the voltage at 1 pu. The voltages in buses 684 and 680 are improved by 0.02 pu using reactive power injection. As a further work, a control

algorithm will be developed for coordinated control and better injected reactive power amount control.
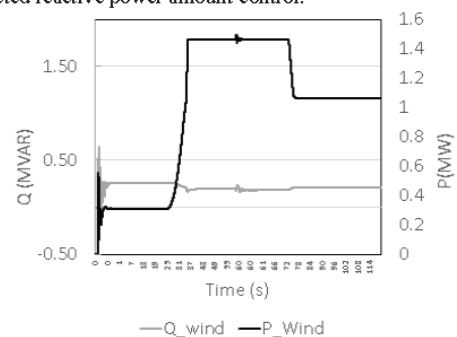

Fig. 12. Case 2 (Wind active and reactive power)
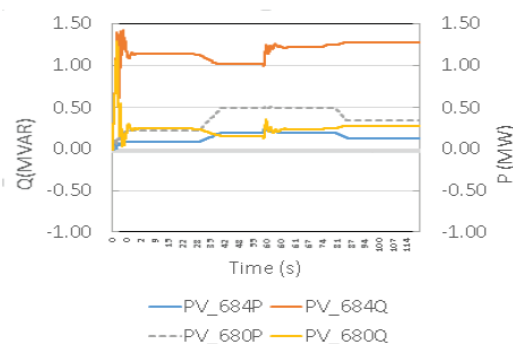

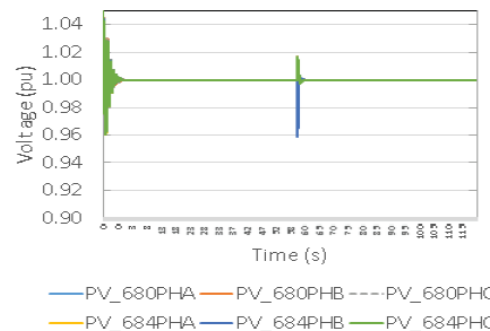Fig. 13. PV 684 and PV 680 active and reactive power.

Fig. 14. Case 2 Voltage in PV 680 and PV 684

D. Case 3

In this case study, the PV systems are not allowed to inject more than 0.075 MVAR which is not enough to regulate voltage at 1 pu. The OLTC and wind turbine have to support the voltage regulation in the distribution system. The voltage drop through the feeders is higher than in Case 2. Fig. 15 shows that the OLTC has to operate and change the tap position to maintain the voltage in bus 632 with an acceptable range. Phase C changes the tap position from 0 to 1 at all the simulation time. The voltage drop in phase A before 60 sec is

not enough for the OLTC to change the tap position. After adding more loads at 60 sec the voltage drop increases then the OLTC changes the tap because the PV systems cannot increase the reactive power injected. In this case, the electrical grid and the wind turbine have to inject more reactive power to support the voltage regulation in the distribution system.
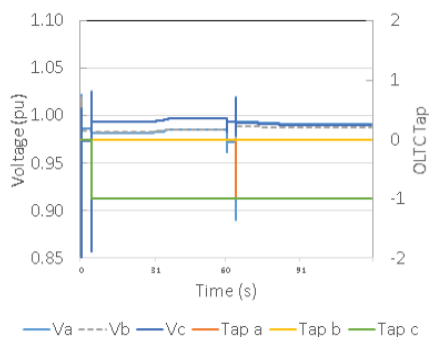

Fig. 15. Case 3 OLTC operations.

Fig. 16 shows the active and reactive power injected from the electrical grid and wind turbine. At 27 seconds the wind speed decreases which decreases the active and reactive power generated from the wind turbine. The electrical grid immediately increases the active power to supply the electrical demand in the system. The electrical grid and wind turbine inject more reactive power than in Case 2 due to the limitation of reactive power injected by the PV systems.
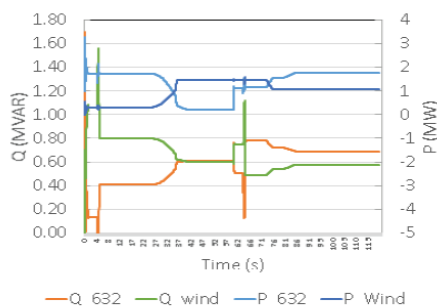

Fig. 16 active and reactive power (Electrical grid & wind turbine)

IV.   CONCLUSION

This paper presented a voltage control of unbalanced distribution system in which distributed PV and single wind turbine, OLTC, capacitor banks exist. IEEE 13 bus system is modelled in Matlab and simulated. Results show that:

- OLTC operation on voltage control is effected with the PV voltage control. PV operated as local controllable reactive power source and provided very precise voltage control. This reduces the OLTC tap changing requirements that increase transformer life time and reduce the losses in the distribution system. No malfunction in the operation is noted. The reduction in the OLTC operation is more significant with each phase voltage control by both OLTC and PV.

- Single phase voltage control of PV can keep the voltage with in the desired levels in unbalanced distribution system as long as it has enough reactive power capacity.

-Each PV unit controls PCC voltage and provides reactive power. However, in the case of many PV systems, coordinated control would be needed.

-Wind turbine has significant impact on distribution system voltage profile. Employing its reactive power control can be beneficial for voltage profile.

-In order to analyze the voltage sinewaves for detailed analysis, inverter models can be used with real time simulators due to the simulation speed and accuracy limitations.

-Dynamic load models can be used as time changing demands to investigate the voltage controller operations.

V.   REFERENCES

[1] R. Caldon, M. Coppo, R. Turri, " Distributed voltage control strategy for LV networks with inverter-interfaced generators," Electric Power Systems Research, vol 107, 2014, pp. 85-92.

[2] United States Energy Information - Us Eia. Annual Energy Outlook 2011.Washington-DC, 2011. Available from, http://www.eia.gov (accessed February 2016).

[3] N. Jayasekara, P. Wolfs, M. A. Masoum, "An optimal management strategy for distributed storages in distribution networks with high penetrations of PV," Electric Power Systems Research, vol. 116, 2014, pp. 147-157.

[4] Danfoss Group Global, "Voltage control in low voltage networks by Photovoltaic Inverters". Nordborg, Denmark. Avaibale http://www.danfoss.com (accessed February 2016).

[5] A. Kechroud, P. F. Ribeiro, W. L. Kling, "Distributed generation support for voltage regulation: An adaptiveapproach," Electric Power Systems Research, vol.107, 2014, pp. 213-220.

[6] J. Hu, M. Marinelli, M. Coppo, A. Zecchino, "Coordinated voltage control of a decoupled three-phase on-load tapchanger transformer and photovoltaic inverters for managing unbalanced networks," Electric Power Systems Research, vol. 131, 2016, pp. 264-274.

[7] C. Long; L. F. Ochoa, "Voltage Control of PV-Rich LV Networks: OLTC-Fitted Transformer and Capacitor Banks," in IEEE Transactions on Power Systems , vol.PP, no.99, pp.1-10

[8] Chao Long, A. T. Procopiou, L. F. Ochoa, G. Bryson and D. Randles, "Performance of OLTC-based control strategies for LV networks with photovoltaics," Power & Energy Society General Meeting, 2015 IEEE, Denver, CO, 2015, pp. 1-5.

[9] A. Navarro-Espinosa and L. F. Ochoa, "Increasing the PV hosting capacity of LV networks: OLTC-fitted transformers vs. reinforcements," Innovative Smart Grid Technologies Conference (ISGT), 2015 IEEE Power & Energy Society, Washington, DC, 2015, pp. 1-5.

[10] H. Ravindra, M. Omar Faruque, K. Schoder, M. Steurer, P. Mclaren and R. Meeker, "Dynamic interactions between distribution network voltage regulators for large and distributed PV plants," Transmission and Distribution Conference and Exposition (T&D), 2012 IEEE PES, Orlando, FL, 2012, pp. 1-8.

[11] Hong-Tzer Yang, Yu-Tang Chen, Jian-Tang Liao and Chiao-Tung Yang, "Over-voltage mitigation control strategies for distribution system with high PV penetration," Intelligent System Application to Power Systems (ISAP), 2015 18th International Conference on, Porto, 2015, pp. 1-6.

[12] IEEE PES Distribution System Analysis Subcommittee's Distribution Test Feeder Working Group. Available at: http://ewh.ieee.org/soc/pes/dsacom/testfeeders/

[13] P. Kang, D. Birtwhistle,"Condition Assessment of Power Transformer On-Load Tap-Changers Using Wavelet Analysis," IEEE Trans. Power Delivery, 2011, pp. 394-400.

CASE 1 MAIN M FILE

```
function obj=OF(vecX)

        %Taking values from GA and assigning to value
        Tap=vecX(1);



 if Tap>0
    set_param('A/OLTC','InitialTap','-1');
end

if Tap<=0
    set_param('A/OLTC','InitialTap','1');
end

        CapOnOff=vecX(2);
        QPV=vecX(3);


        %setting parameters on model with value from GA
        set_param('A/Constant','value',num2str(Tap));
        set_param('A/Constant2','value',num2str(CapOnOff));
        set_param('A/Constant3','value',num2str(QPV));

        %Simulation and capturing the output
        simOut=sim('A','SaveOutput','on','OutputSaveName','values');
        z=simOut.get('values');
        Fvalues=z(:,1);
        Fvalues=Fvalues(end);

        % Setting up the obj function
         obj=Fvalues; % (+) means min => CapOnOff=0 , (-) means max =>
         CapOnOff=1..

  end
```

CASE 1 PI PARAMETERS M FILE

```
  function [ c, ceq ] = nlc( Vol )

        %Simulation and capturing the output
        simOut=sim('A','SaveOutput','on','OutputSaveName','values');
        z=simOut.get('values');
        Voltage=z(:,2);
        Voltage=Voltage(end);

        % Setting up the obj function
        Vol(1)=Voltage;
```
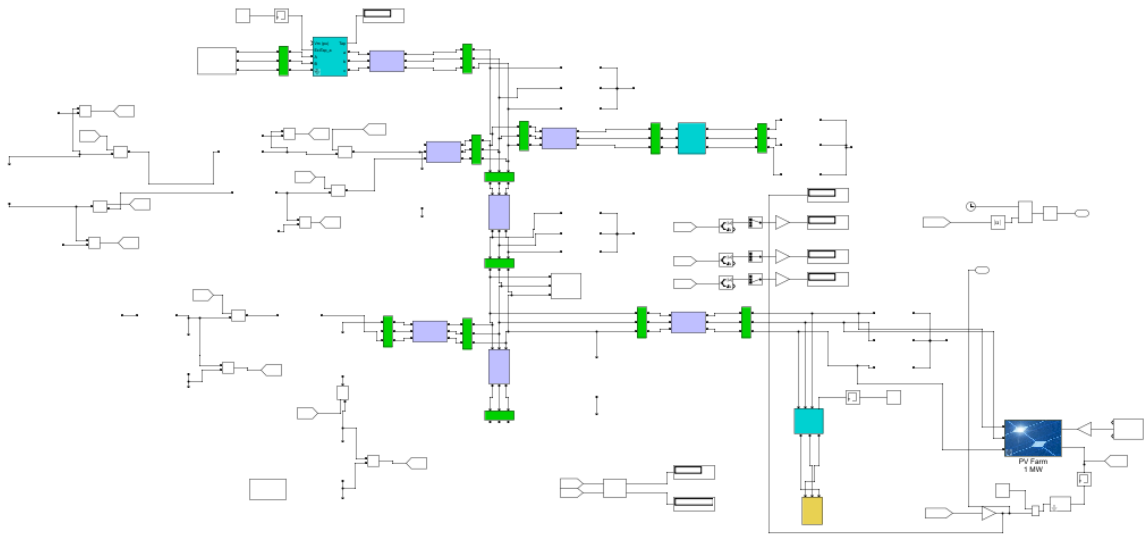
```
%c = [(-Vol(1)+0.95) (Vol(1)-1.05) ];
c(1) = -Vol(1)+0.95;
c(2) = Vol(1)-1.05;
ceq = [];

end
```

CASE 2

CASE 2 MAIN M FILE

```
function [ c, ceq ] = IEEEbusnlc( pid )

    IEEE13bus03
    TT = pid(1);
    CC = pid(2);
    Kppv = pid(3);
    Kipv = pid(4);




    %Simulation and capturing the output
    myobj = sim('IEEE13bus03','SrcWorkspace','Current', ...
    'StopTime','10');
```

```
        c=zeros(length(myobj.yout),2);

for i=1:1:length(myobj.yout)

        Vol=myobj.yout(i);
        c(i,1) = -Vol+0.95;
        c(i,2) = Vol-1.05;
        ceq =[];

end
```

CASE 2 PI PARAMETERS M FILE

```
function obj = IEEEbus(pid)
      TT = pid(1);
      CC = pid(2);
      Kppv = pid(3);
      Kipv = pid(4);




if TT>0
   set_param('IEEE13bus03/OLTC','InitialTap','-1');
end

if TT<=0
   set_param('IEEE13bus03/OLTC','InitialTap','1');
end



myobj = sim('IEEE13bus03','SrcWorkspace','Current', ...
        'StopTime','10');

obj=myobj.yout(end,2);

end
```
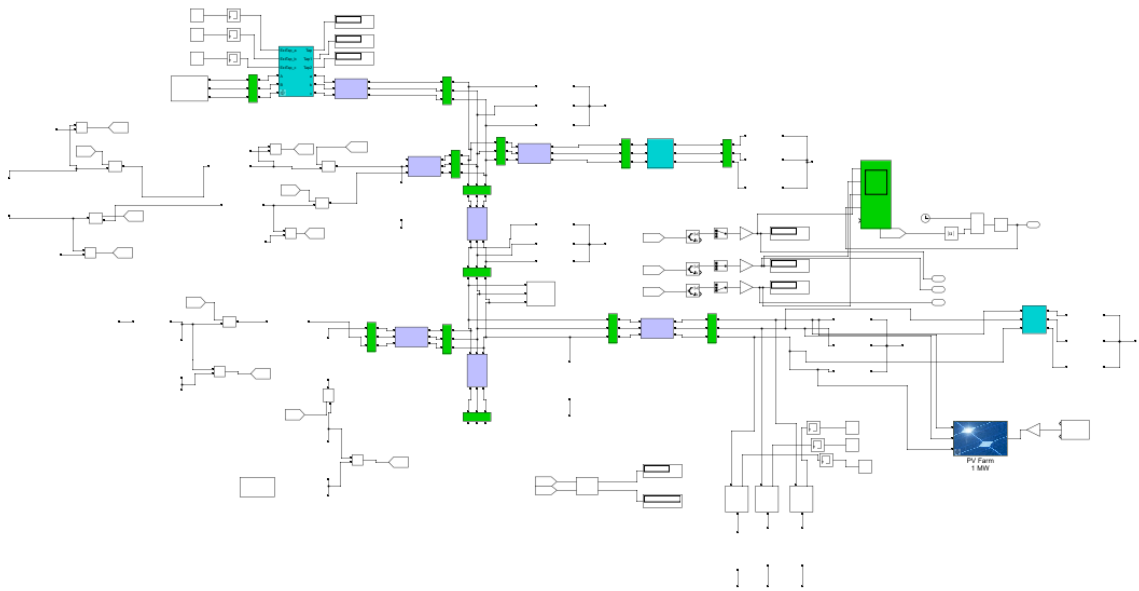
CASE 3

CASE 3 MAIN M FILE

```
function obj = IEEEbus(pid)
      TT_a = pid(1);
      CC_a = pid(2);
      TT_b = pid(3);
      CC_b = pid(4);
      TT_c = pid(5);
      CC_c = pid(6);
      Kppv_a = pid(7);
      Kipv_a = pid(8);
      Kppv_b = pid(9);
      Kipv_b = pid(10);
      Kppv_c = pid(11);
      Kipv_c = pid(12);


if TT_a>0
   set_param('IEEE13bus03/OLTC','InitialTap_a','-1');
end

if TT_a<=0
   set_param('IEEE13bus03/OLTC','InitialTap_a','1');
end
```

```
if TT_b>0
   set_param('IEEE13bus03/OLTC','InitialTap_b','-1');
end

if TT_b<=0
   set_param('IEEE13bus03/OLTC','InitialTap_b','1');
end


if TT_c>0
   set_param('IEEE13bus03/OLTC','InitialTap_c','-1');
end

if TT_c<=0
   set_param('IEEE13bus03/OLTC','InitialTap_c','1');
end


myobj = sim('IEEE13bus03','SrcWorkspace','Current', ...
       'StopTime','10'); %0.05

obj=myobj.yout(end,1);

 end
```

CASE 3 PI PARAMETERS M FILE

```
function [ c, ceq ] = IEEEbusnlc( pid )

    IEEE13bus03

    TT_a = pid(1);
    CC_a = pid(2);
    TT_b = pid(3);
    CC_b = pid(4);
    TT_c = pid(5);
    CC_c = pid(6);
    Kppv_a = pid(7);
    Kipv_a = pid(8);
    Kppv_b = pid(9);
    Kipv_b = pid(10);
    Kppv_c = pid(11);
    Kipv_c = pid(12);
    %Simulation and capturing the output
      myobj = sim('IEEE13bus03','SrcWorkspace','Current', ...
      'StopTime','10');
```
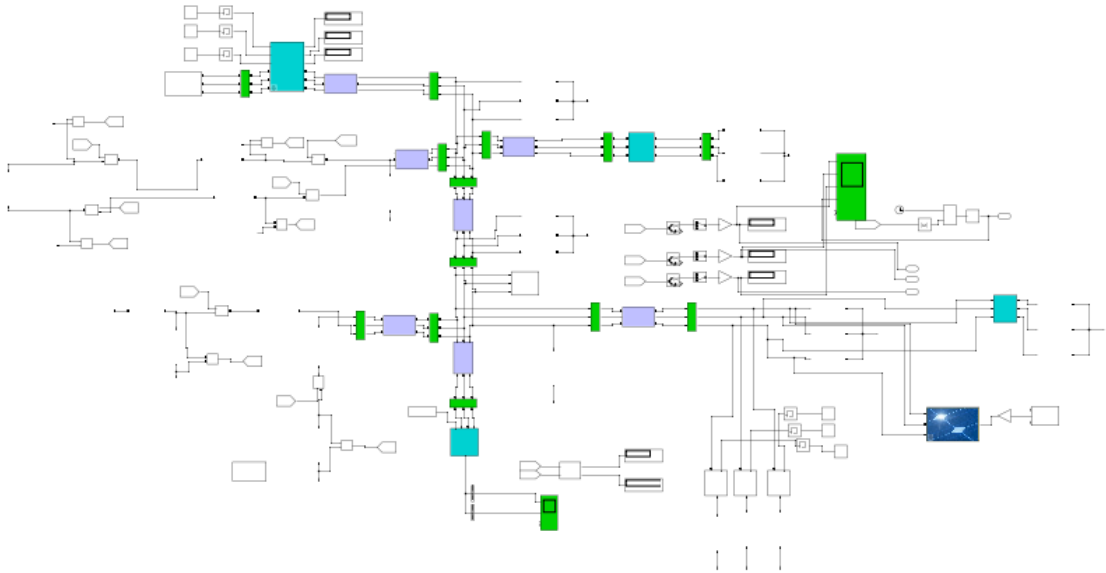
```
        c=zeros(length(myobj.tout),6);

for i=1:1:length(myobj.tout)

        Vola=myobj.yout(i+length(myobj.tout));
        c(i,1) = -Vola+0.95;
        c(i,2) = Vola-1.05;

        Volb=myobj.yout(i+2*length(myobj.tout));
        c(i,3) = -Volb+0.95;
        c(i,4) = Volb-1.05;

        Volc=myobj.yout(i+3*length(myobj.tout));
        c(i,5) = -Volc+0.95;
        c(i,6) = Volc-1.05;

        ceq =[];

end

end
```

CASE 4

CASE 4 MAIN M FILE

```matlab
function [ c, ceq ] = IEEEbusnlc( pid )

      IEEE13bus03

      TT_a = pid(1);
      CC_a = pid(2);
      TT_b = pid(3);
      CC_b = pid(4);
      TT_c = pid(5);
      CC_c = pid(6);
      Kppv_a = pid(7);
      Kipv_a = pid(8);
      Kppv_b = pid(9);
      Kipv_b = pid(10);
      Kppv_c = pid(11);
      Kipv_c = pid(12);


        %Simulation and capturing the output
        myobj = sim('IEEE13bus03','SrcWorkspace','Current', ...
        'StopTime','10');


      c=zeros(length(myobj.tout),6);
for i=1:1:length(myobj.tout)

      Vola=myobj.yout(i+length(myobj.tout));
      c(i,1) = -Vola+0.95;
      c(i,2) = Vola-1.05;

      Volb=myobj.yout(i+2*length(myobj.tout));
      c(i,3) = -Volb+0.95;
      c(i,4) = Volb-1.05;

      Volc=myobj.yout(i+3*length(myobj.tout));
      c(i,5) = -Volc+0.95;
      c(i,6) = Volc-1.05;

      ceq =[];

end
end
```

CASE 4 PI PARAMETERS M FILE

```
function obj = IEEEbus(pid)
      TT_a = pid(1);
      CC_a = pid(2);
      TT_b = pid(3);
      CC_b = pid(4);
      TT_c = pid(5);
      CC_c = pid(6);
      Kppv_a = pid(7);
      Kipv_a = pid(8);
      Kppv_b = pid(9);
      Kipv_b = pid(10);
      Kppv_c = pid(11);
      Kipv_c = pid(12);
if TT_a>0
   set_param('IEEE13bus03/OLTC','InitialTap_a','-1');
end

if TT_a<=0
   set_param('IEEE13bus03/OLTC','InitialTap_a','1');
end

if TT_b>0
   set_param('IEEE13bus03/OLTC','InitialTap_b','-1');
end

if TT_b<=0
   set_param('IEEE13bus03/OLTC','InitialTap_b','1');
end

if TT_c>0
   set_param('IEEE13bus03/OLTC','InitialTap_c','-1');
end

if TT_c<=0
   set_param('IEEE13bus03/OLTC','InitialTap_c','1');
end

myobj = sim('IEEE13bus03','SrcWorkspace','Current', ...
        'StopTime','10'); %0.05

obj=myobj.yout(end,1);

    end
```