Department of Electrical and Computer Engineering

Coordination of Single-Phase Rooftop PVs in Unbalanced Three-phase Residential Feeders for Voltage Profiles Improvement

Nelly Safitri

This thesis is presented for the Degree of

Doctor of Philosophy

of

Curtin University

February 2015

Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: 

Date: 29/03/2016

ACKNOWLEDGMENT

I would like to express my special thanks to my supervisor, Professor Mohammad A.S. Masoum, for his invaluable advice, guidance and support all throughout my PhD studies. I am also greatly thankful to my co-supervisor, Dr. Farhad Shahnia for his assistance during the course of my study. Finally, financial support from DIKTI - Indonesia Ministerial of Higher Education, Research and Technology is gratefully acknowledged. Also greatly thankful to my employer, Lhokseumawe State Polytechnic, Aceh – Indonesia. Last but not least, I wish to express my love and gratitude to my husband and son and family and friends for their endless support and love.

ABSTRACT

The application of rooftop PVs in distribution networks is gaining increasing popularity in most developing countries including Australia. Uneducated placement of rooftop PVs with various ratings along the single-phase residential feeders may deteriorate network voltage profile. In addition, the multiple PV inverters injecting or absorbing reactive power across a distribution feeder may introduce control interactions and/or voltage unbalance issues. The focus here is to investigate the potential and possibility of distributed reactive power control in single-phase feeders to improve the voltage profile and reduce the voltage unbalance of three-phase radial distribution networks. A new algorithm based on the droop control will be implemented to coordinate the reactive power injections of single-phase rooftop PVs in order to regulate network voltages and reduce the voltage unbalance factor. The load flow analysis is carried out to investigate the effects of rooftop PVs on three-phase network voltage profiles. It simulates a voltage droop control that maintains the steady state voltage profiles close to the reference values, up to a certain level of loading. This focus will be the basic fundamental of this thesis development.

Utilization of rooftop PVs in residential feeders without controlling their ratings and locations may deteriorate the overall grid performance including power flows, losses and voltage profiles. The investigation of the potential and possibility of a distributed reactive power control and active power curtailment by rooftop PVs in

three-phase unbalanced low voltage residential feeders in a smart grid concept will be one of the main focuses in this thesis.

Then, the investigation of different methods for regulating the voltage profile and reducing the voltage unbalance at low voltage residential feeders is another focuses of this thesis. The algorithm considers reactive power exchange and active power curtailment of the single-phase rooftop PVs. In addition, it is assumed that the distribution transformers have on-load tap changers and can automatically control the voltage to prevent voltage rise in the feeder.

The last focuses of this thesis is investigating the effectiveness and limitations of a voltage profile regulating method composed of three different techniques. The method is applicable for LV residential feeders with single-phase rooftop PVs and relies on the availability of smart meters at the buses along the LV feeder to transmit phase voltage measurements to the controllers of the PV inverters. The first objective of the method is to minimize non-standard voltage rise along the feeder by reducing the voltage at the secondary of the distribution transformer. This is achieved by utilizing a distribution transformer with on load tap changing capability and a master controller located at the transformer. The algorithm also considers reactive power exchange and active power curtailment by the inverters of the single-phase rooftop PVs as the main steps for voltage profile regulation. The main purpose of the method is to improve the voltage profile while the second purpose is to reduce the voltage unbalance along the feeder. Simulation results will be generated and analysed for an unbalanced three-phase distribution network populated with rooftop PVs using Matlab software. The communication concept though will not discuss thoroughly in this thesis, but plays the important roles due to coordinate PV inverter along the LV feeder. The concept is the two way flow of information which was developed to provide reliable and high quality electric power to meet with customer demands. This process indicates changing the control and dealing with a mutual data information exchange system which will enable to accommodate PV inverters without disturbing the efficiency of the power flow.

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Statement of Problem

The increasing demand for energy followed by the need for cost reduction and requirements for more consistency has initiated an increase renewable energy production over the last decade. Alternative energy sources such as solar, wind and hydro have shown to be most popular, mostly because they are limitless and yield no emission. Photovoltaic (PV) technology is the most rapidly growing renewable resource technology since it was first used as power supply for satellites [1]. The utilization of PV in the grid-connected residential low voltage (LV) distribution feeder is increasing around the world. Many countries have promoted PVs in distribution feeders [2]. However, since most LV distribution networks were constructed a few decades ago and are reaching their capacity limits due to natural load growth, the customer load demand and power quality expectations have increased considerably along with a rapid growth in the digital technology [3].

The utilization of PV at the residential LV distribution level does not come without technical challenges. One of the main issues is the power quality of the system, mostly regarding voltage unbalance (VU) and voltage profile regulation. Voltage unbalance commonly occurs in individual customer load due to unequal distribution of single-phase loads, specifically when large single-phase power load are used [4]. In the other words, the voltage profile of the three phases is different since the rooftop PVs are installed randomly along the feeders and with various ratings. As the difference in amplitude between the phases is high, the VU rises [2]. In reference [5] the VU will have the most significant effect at the end of the feeder as it could exceed the allowable limit [6]. Additionally, the installation of rooftop PVs along the feeder will create VU that will be changed on all the feeders of the network. Meanwhile, the integration of massive amounts of rooftop PVs in the LV networks increases the generation of active power leading to voltage rise along the feeders. Currently the voltage rise does not go beyond the 2% limit imposed by the IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems. However, it is expected in the future that the voltage limit will be beyond 3% [6].

Conventional improvement methods can be applied to improve voltage profile and reduce voltage unbalance. Parallel and series converter-based custom power devices (CPD) have been widely utilized due to improved power quality [7]. Reference [8], CPD such as dynamic voltage restorer (DVR) and distribution static compensator (DSTATCOM) are used for voltage correction within the network and for voltage profile and voltage unbalance improvements, DSTATCOMs are more efficient than DVRs.

This thesis proposes two voltage control strategy approaches to possibly regulate voltage profile and reduce voltage unbalance in the three-phase residential LV network with rooftop PVs: (1) Utilization of the on-load tap changing (OLTC) feature of transformers is an effective method for controlling the secondary voltage of transformer and hence regulating the voltage profile. The voltage control can take the actual load state of the transformer and the network into consideration; (2) Using the extra capacity of PVs by exchanging their reactive power and curtailing the active power by single-phase PV approaches can be applied for voltage amplitude control within the network; (3) The two proposed methods and utilization of OLTC feature of the distribution transformer can be applied together within an optimization concept to achieve better results.

1.2 Literature Review

In this sub section, a comprehensive literature review is carried out to (1) determine the rooftop PVs, droop control concept, OLTC feature of transformer, reactive power exchange and active power curtailment techniques by single-phase rooftop within the three-phase residential LV networks; (2) investigates the possibilities of using those techniques to regulate voltage profile and reduce voltage unbalance. For this purpose, it is assumed that proper voltage monitoring and transmitting devices are available throughout the feeders to provide data transfer among the controllers of the rooftop PV inverters.

1.2.1 Rooftop PVs

According to Australian Standard Voltages, AS60038-2000, Australian LV network is 230V, and its tolerance is in the range of +10% to -6% [9]. As the future LV networks' substantial feature, grid-connected rooftop PV has shown significant benefits for both utilities and individual customers. In fact, currently, rooftop PVs are being installed depend on the attitude and financial circumstance of householders. It is obvious that these installations of rooftop PVs are randomly located along the feeders. Therefore, it is possible if in the three-phase network feeder circumstances, most customers on a phase have installed rooftop PVs, while the other two phases have less installation of rooftop PVs. In such circumstances, the standard voltage imbalance of the network cannot guarantee to remain so. For that reason, it is possible that the rooftop PVs installation along the LV network feeder might have a significant influence the unbalance voltage occurs.

LV networks with high penetration of rooftop PVs can encounter two main power quality challenges. PVs inject active power based on a maximum power point tracking (MPPT) algorithm in unity power factor (UPF) recommended by the IEEE Recommended Practice for Utility of Photovoltaic System [10]. When rooftop PVs are utilized in LV networks, we may still experience voltage drop along the network during peak load period [11]. This is because during noon periods, rooftop PVs usually generates their maximum power, while the load demand in the network is at its minimum level. The high power generation by rooftop PVs can cause voltage rise in the network and force the voltage to exceed the maximum allowable limits [12].

As mentioned earlier, the randomly installed residential rooftop PVs across distribution systems can cause significant problems in the three-phase LV feeder. This may lead to an increase in unbalance index of the network and will cause problems for three-phase loads, for example motors for pumps and elevators. Reference [13], [14] have conducted investigations of several technical problems of European and UK distribution networks for maximum tolerable numbers of PVs in the networks.

Reference [15] has investigated the voltage unbalance issue at different locations along the LV feeders populated with rooftop PVs based on a Monte Carlo method. This research indicates that PV installations will have a minor effect on the voltage unbalance at the beginning of an LV feeder designed with engineering judgments; however, the voltage unbalance might increase at the end of the feeder to more than the standard limit. Reference [16] has analysed the voltage variation sensitivity due to PV power fluctuation in unbalanced line configuration and phase loading levels in the network. This research is carried out based on many factors such as up-stream sources, phase loads, PV power fluctuation, distribution line length, phase sequences, line geometries and conductor types.

Reference [17] shows that rooftop PV inverters, when controlled in droop reactive power mode, can improve the voltage profile in a low voltage feeder. In this method, the PV inverters control their output voltages to a fixed value by exchanging reactive power with the feeder. Reference [18] utilizes the droop-based active power curtailment to prevent overvoltage conditions in radial low voltage feeders. The most common mode of voltage regulation in high voltage networks is the application of transformers with on-load tap changers (OLTC) [19].

In this thesis, rooftop PVs are accurately modelled based on their injected active and reactive powers (P_{PV}, Q_{PV}) and their terminal voltages ($|V_{PV}|,\ \delta_{PV}$) as shown in Figure 1.1, with a constant power factor of 0.95 is assumed for each household.

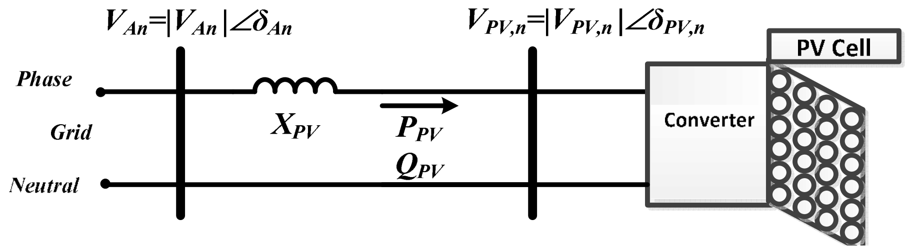

Figure 1.1. Schematic diagram of the rooftop PVs connect to grid

As the voltage imbalance appears beyond its standard limit, hence discussion regarding voltage imbalance will be presented briefly in this section. Voltage imbalance in three-phase network system is a condition in which the three-phase voltages differ in magnitudes and angles. The angles have 120^o phase differences. It is states in the IEEE Recommended Practice for Monitoring Electric Power Quality that voltage imbalance is defined as [20]

$$VUF\% = \left|\frac{V_-}{V_+}\right| \times 100 \qquad 1.1$$

where V_- and V_+ are the negative and positive sequence of voltage, respectively. It is also states in [20], the acceptable limit for voltage imbalance is 2% in LV network.

For calculating voltage imbalance, the analysis of the network has to be considered and voltages at the certain nodes also have to be calculated. The KCL based on *k*th node of for example phase-A can be assumed as

$$\frac{\beta(V_{A,PV,n}-V_{A,n})}{X_{A,PV,n}}+\frac{V_{A,n-1}-V_{A,n}}{Z_f}+\frac{V_{A,n+1}-V_{A,n}}{Z_f}+\frac{V_{N,n}-V_{A,n}}{Z_{A,L,n}}=0 \quad 1.2$$

where the controlling constant β is equal to 1 when there is a PV connected to *k*th node, otherwise, it is zero. $V_{A,PV,n}$ and $X_{A,PV,n}$ are the PV voltage and impedance that connected to *n*th node of phase-A, respectively. $V_{A,i}$, $i =$ 1,…, n is the single-phase voltage of the *i*th node of phase-A and Z_f is the feeder impedance between two adjacent nodes in phase line. $V_{N,n}$ is the voltage of the neutral wire connected to *n*th node and $Z_{A,L,n}$ is the load impedance that connected to *n*th node of phase-A. Similar equations occur for phase-B and phase-C. The KCL for each node on the neutral line is as follow

$$\frac{V_{N,n-1}-V_{N,n}}{Z_n}+\frac{V_{N,n+1}-V_{N,n}}{Z_n}+\frac{V_{N,n}-V_{A,n}}{Z_{A,L,n}}+\frac{V_{N,n}-V_{B,n}}{Z_{B,L,n}}+\frac{V_{N,n}-V_{C,n}}{Z_{C,L,n}}=0 \quad 1.3$$

Where Z_n, is the feeder impedance between two adjacent nodes in neutral line.

The large application of rooftop PVs as single-phase and three-phase distributed generators has been packed as the future utilities' packet as it envisioned in [21]. The possible formal results, opportunities and challenges, for the use of PV in zero energy building (ZEBs), as well as new research issues for the future relationships between PV and ZEBs from the architecture and landscape design point of view. The power flow approach also developed in such way as discussed in [22]. It preserves the original 3-wire and 4-wire configurations for more accurate estimation of rooftop PV impacts on different phases and neutrals. Several benefits and drawbacks of PV system in the LV network can be seen briefly in table 1.1.

Table 1.1. Benefits and drawbacks of PV
(adapted from
http://www.energybc.ca/cache/solarpv/www.cetonline.org/Renewables/PV_pro_con.html, accessed by 15 May 2015)

Benefits of PV
• PV systems provide green, renewable power by exploiting solar energy. It can be used as an alternative energy source in place of electricity generated from conventional fossil fuels. • PV panels constitute a reliable, industrially matured, green technology for the exploitation of solar energy. Several PVs' companies provide valuable warranties for PV panels in terms of both PV panel life span and PV efficiency levels across time. PV panels can last up to 25 years or more, some with a maximum efficiency loss of 18% only, even after 20 years of operation. • Unlike wind turbines, PV panels operate autonomous without any noise generation as they do not incorporate any moving mechanical parts. Furthermore, in adjustable PV systems, the movements are very moderate, almost negligible, and do not generate any disturbances. • With respect to operating costs and maintenance costs, PV panels do not require operating or maintenance costs. • PV panels can be ideal for distributed power generation as they are highly suitable for remote applications, such as in a remote farmhouse. By maintaining relatively small power generation stations in a distributed power network, it can minimize energy losses in the network that are caused by the long distance between power generation and power consumption points.
Drawback of PVs
• The biggest disadvantage of PV panels is their limited efficiency levels; compared to other renewable energy sources – such as solar thermal – PV systems have a relatively low efficiency level in the range of 12-20%.

1.2.2 Droop Control Concept

Another developing method to regulate the voltage profile network is the droop control method. Droop control of ac sources involves lowering of voltage frequency f and voltage amplitude V, whenever increases in active power P and reactive power Q are sensed [23-24]. Many references define and describe droop control. Some of them are related to this proposed approach such as the droop line concept which can be used to share real and reactive power compensation as unbalance and harmonic compensation [25]. Reference [26] utilizes the droop-based active power curtailment to prevent overvoltage conditions in radial low voltage feeders. Reference [27] introduces a method that states a small signal can be modelled in the active droop control method of a two-loop feedback control system (designed for the active droop control) to achieve good and high efficiency transient response. Based on [28], the frequency and voltage control, including mitigation of voltage harmonics can be achieved without the need for any common control circuitry or communication between inverters. An application of droops in LV grids has been researched in good manner that shown that the droops that are used in the interconnected grid can be effectively utilized on the LV level due to their indirect operation [29].

Droop control approach is commonly applied for lowering the frequency and voltage amplitude whenever increases in active and reactive powers are sensed. When rooftop PVs are deployed in single-phase residential feeders, the normal electric power demand pattern will change and the three-phase power system might not be capable of handling the new operating conditions and demands.

For simplicity, hence an example of droop control through active and reactive power injection (Figure 1.2) can be performed with rooftop PVs based on their equivalent circuit (Figure 1.1) and power characteristics highlighted by equation 1.3 and 1.4.

$$P_{PV} = \frac{|V_{An}||V_{PV}|sin(\delta_{An}-\delta_{PV})}{X_{PV}}, \quad Q_{PV} = \frac{|V_{An}||V_{PV}|cos(\delta_{An}-\delta_{PV})-|V_{PV}|^2}{X_{PV}} \quad 1.4$$

From (1.1), then δ_{An} and $|\boldsymbol{V_{An}}|$ can be computed.

$$\delta_{An} = \delta_{PV} + atan\left(\frac{P_{PV}.X_{PV}}{Q_{PV}.X_{PV}+|V_{PV}|^2}\right), \quad |V_{An}| = \frac{P_{PV}X_{PV}}{|V_{PV}|sin(\delta_{PV})} \quad 1.5$$

According to Figure 1.2, adjusting $\delta_{An} - \delta_{PV}$ might change the active power to its higher or lower values, then adjusting Q changes the difference of $V_{An} - V_{PV}$ as well:

$$\delta_{An} - \delta_{PV} = -K_p(P_{ref} - P_{PV}), \quad V_{An} - V_{PV} = -K_q(Q_{ref} - Q_{PV}) \quad 1.6$$

where K_p and K_q are the droop coefficient for active and reactive power, respectively.

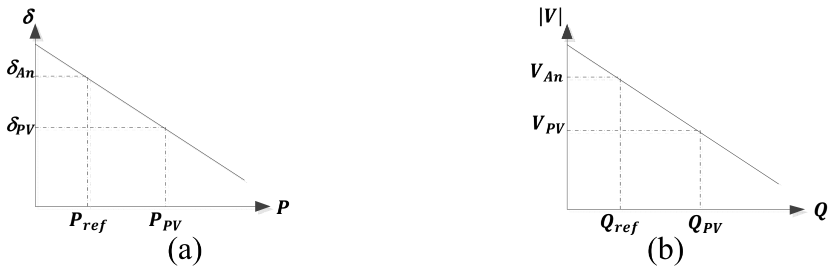

Figure 1.2. The droop concept; (a) δ-P characteristics, (b) V-P characteristics

Voltage improvement and regulation through droop control of the rooftop PV's inverters will only be effective up to a certain level of loading. Therefore, modifying the droop based concept into reactive power exchange and active power curtailment by PV inverter and in such a way are combined together to achieve to regulate voltage profile and reduce voltage unbalance along the LV feeder.

1.2.3 On Load Tap Changer Transformer

Power transformers featuring on-load tap-changers (OLTCs) have been the main components of electrical networks and industrial applications for nearly 90 years. OLTCs enable voltage regulation and/or phase shifting by varying the transformer ratio under load condition without interruption. The OLTC changes the ratio of a transformer by adding or subtracting and turns from either the primary or the secondary winding. Therefore, the transformers are equipped with a regulating or tap winding components which is connected to the OLTC [30].

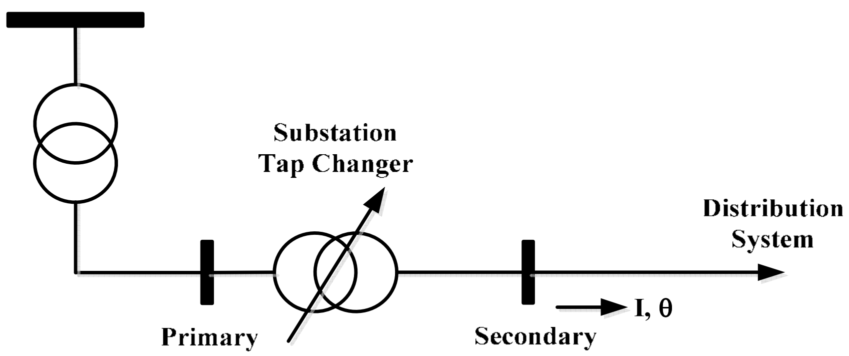

Figure 1.3. Topology of distribution system with OLTC transformer feature at the substation [31]

As can be seen in Figure 1.3, when the transformer substation of the distribution system equipped with OLTC feature, this OLTC is used to change the tapping connection of the transformer winding to change the voltage ratio while the transformer is still in service without interrupting the load [32]. An on-load tap-changer gear comprises two major components, the tap selector and the diverter switch. The tap selector selects the tapping and its electrical contacts are designed to carry the rated current of the transformer without making or breaking this current. The diverter switch, however, needs to be designed to carry, make and break the load current in circuits previously selected by the tap selector. During the operation of the diverter switch, the transition resistors bridge the gap in use and the tap next to be used, thereby limiting the circulating current due to the inter-tap voltage [33]. OLTC are widely used for voltage regulation and also as phase-shifting transformers.

Recently, the application of OLTC was conventionally limited to HV/HV or HV/MV transformers, while the small, low-cost distribution transformers did not warrant the expense and complexity of OLTC and were thus normally provided with off-circuit taps. This arrangement enabled the tap positions to be adjusted to suit the network conditions, usually when the transformer was initially placed into service. However, the facility enabled adjustments to be made subsequently, when possible changes to the network loading necessitated this [33]. Typically, distribution transformers implement a no-load tap changer (NLTC) mechanism to adjust the feeders' static voltage set point. It is noted that the NL TC operates on the primary transformer winding [34].

Transformers with OLTC are very expensive and only limited to high voltage networks. However, a traditional distribution transformer can be modified to act as a low voltage (LV) OLTC transformer by adopting semiconductor devices. In such a condition, an LV distribution with OLTC can regulate the voltage profile in the network [33]. Voltage profile along the LV feeder should be kept within the recommended limits of 95% and 110% of the nominal voltage [35]. By utilizing a transformer with OLTC, the turn ratio of the transformer is adjustable. As the OLTC of the transformer can be equipped with the automatic voltage control (AVC) relays and known as the most popular and effective voltage control device, STATCOM, power factor generator are also the useful technique to control the voltage in distribution system [36]. An independent control scheme for the voltage regulation of STATCOM is proposed in [37] which based on the schematic control of based on the feedback of processed line voltages to the reference voltage input of STATCOM due to reduce the compensation output when the terminal voltage is in its steady state. However, it still can provide high compensation output when there is an abnormal low voltage contingency in the upstream.

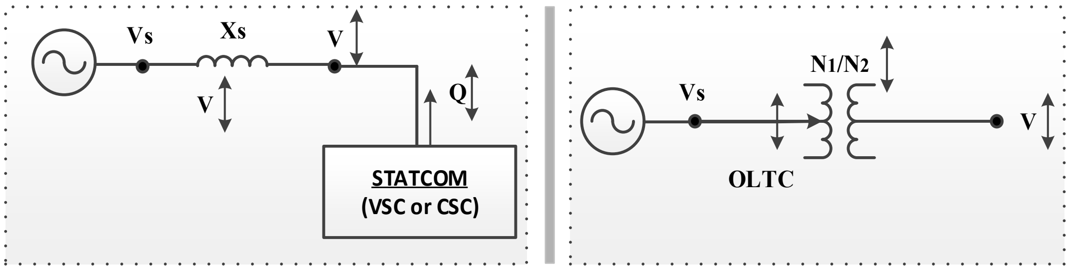

Figure 1.4. Basic Structure and mechanism of STATCOM and transformer OLTC feature [37]

Figure 1.4 illustrates the basic structure and mechanism of STATCOM and OLTC of the transformer as they regulate the voltage to steady at the allowable limits.

Moreover, the optimal reactive power coordination strategy based on the load and irradiance forecast due to minimize the number of tap operations so as not to reduce the operating life of the tap control mechanism and avoid runaway is proposed in [38]. The achievement of this method described by coordinating various reactive power control options in the distribution network while satisfying constraints such as maximum power point tracking of PV and voltage limits of the feeder. The option of voltage support from PV plant is also considered.

More recent studies which have been investigated the utilization of OLTC feature of the transformer to will discuss comprehensively in Chapter 3, as they support contents of the chapter.

1.2.4 Reactive Power Exchange

The increasing appetite for the installation of distributed DG units such as rooftop PVs can change the direction of power flow and lead to voltage regulation problems. In addition, most of the residential rooftop PVs are single-phase units. Their integrations into the three-phase networks might also cause unbalance issues due to their random location and rating. This might lead to an increase in voltage beyond the standard value [2], [13].

According to the interconnection standard for distributed generation [34], PV inverters may not inject or consume reactive power or attempt to regulate voltage in any way, i.e. they must operate at unity power factor while in grid-connected mode. To overcome voltage regulation problems anticipated on distribution circuits with high penetrations of PV generation, these regulations are expected to be changed to allow the injection of reactive power.

One of the most commonly used voltage control strategy methods to overcome the voltage rise problem when no storage units are installed, but only local point common coupling (PCC) measurements are utilized in the network, is VSCs-based control of reactive power injection/absorption, and distributed PV based can contribute to network voltage as both dynamically and statically [39]. In [40], it was shown that a PV can be controlled so that it regulates its output voltage by exchanging reactive power. This can significantly reduce the voltage rise in the network. Reference [41] studies that fast-reacting, VAR-capable PV inverters may provide the necessary reactive power injection or consumption to maintain voltage regulation under difficult transient conditions. As a side benefit, the control of reactive power injection at each PV inverter provides a new tool for distribution utilities to minimize the thermal losses in circuit.

More detail about recent studies which mitigate the reactive power support by PV inverters along LV network due to regulate voltage profiles will discuss comprehensively in Chapter 4, as they support contents of the chapter.

1.2.5 Active Power Curtailment

Due to high *R/X* values in LV networks, reactive power alone cannot keep the voltages in the permissible range [42]. For this reason, the contribution of active power is also needed to have a robust voltage rise control. One can use active power curtailment techniques to reduce the amount of active power injected by the PV inverters, as the voltage at their buses increases beyond its allowable value. In this manner, it is possible to increase the installed PV capacity and energy yield while preventing overvoltage [43]. The option of active power curtailment appears very attractive because it requires minor modifications in the inverter control logic. Moreover, it is only activated when needed thus minimizing the amount of curtailed active power [44].

More detail about recent studies which mitigate the active power curtailment technique by PV inverters along LV network in order to reduce voltage unbalance will discuss comprehensively in Chapter 5, as they support contents of the chapter.

1.3 Research Objective

The main objective of this thesis is to investigate and implement the coordination of rooftop PVs and utilization of OLTCs in an unbalanced three-phase residential LV network at difference penetration levels and ratings of PVs. A load flow algorithm will be generated in Matlab that utilizes the distributed reactive power control and active power curtailment of PV approaches to maintain the steady state single- and three-phase voltage profiles close to the designated reference values, up to a certain level of loading to simultaneously achieve the following main objectives:

- Reducing the impact of injected reactive power to the network by rooftop PVs.

- Utilizing the distributed reactive power control and active power curtailment of PV approaches to maintain the voltage profile within the acceptable limits.
- Coordinating PVs and utilizing OLTCs and proposed approaches to further regulate network voltage profiles and reduce voltage unbalance.

1.4 Thesis Contribution

This thesis investigates and implements the possibility of coordinating single-phase PVs in unbalance three-phase residential LV network at difference penetration levels and ratings of PVs in order to maintain the steady state single-phase voltage profiles close to the designated reference values, up to a certain level of loading to simultaneously achieve the main objective, which is to coordinate PVs to further regulate network voltage profiles and reduce voltage unbalance.

A load flow algorithm will be generated in Matlab that utilizes the approaches of reactive power exchange and active power curtailment by PVs, and also the adjustment of the OLTC feature of the distribution transformer due to maintaining the voltage profile within the allowable limits, also providing the voltage unbalance reduction.

1.5 Thesis Structure

This thesis consists of seven chapters. Chapter 1 discusses the three-phase residential LV feeder with single-phase rooftop PVs and the problems associated with it. Moreover, it also discusses the enhancement of the voltage profile regulation, the reduction of voltage unbalance and proposed approaches when conducting the coordination of rooftop PVs at difference penetration levels and ratings in the network. These indices will be compared and applied to different situations in later chapters through extensive simulations.

Chapter 2 presents the problem formulation and network under consideration, as well as the droop control method which has been simply applied to maintain voltage profiles within acceptable limits and reduce the impact of injected reactive power to the network by rooftop PVs. Chapter 3 discusses the reactive power exchange performances and limitations for unbalanced three-phase distribution networks in which PVs are installed at different locations and ratings. The voltage profiles of this method based will be compared through simulation studies.

In chapter 4, the coordination of rooftop PVs will be applied by using the active power curtailment by PVs approach. The implementation of this proposed method will be described differently in order to highlight the performance and limitations of each simulation study and provide the solutions to overcome them. Chapter 5 describes the utilization of OLTCs in order to demonstrate their performance and limitations for maintaining voltage profiles within acceptable limits and reduce voltage unbalance. Chapter 6 describes the comparison and combinations of both mentioned approaches plus the utilization of the OLTC feature of distribution transformer and determination of proper approaches for proper case studies. Finally, conclusions and suggestions for future research are presented in Chapter 7.

CHAPTER 2

MODELLING OF THE RESIDENTIAL THREE-PHASE LOW VOLTAGE NETWORK WITH ROOFTOP PVs

The critical factors in residential three-phase low voltage distribution networks with rooftop PVs (single- and three-phase) are high performance, coordination and consistency. The penetration of installed PVs systems within the network depends on the locations and ratings. However, the evolving rooftop PVs and loads experience daily and seasonal variations that will result in several operational problems, such as unacceptable voltage profile and insufficient electricity demand [45-46]. For that reason, even the mentioned distribution network classified as an LV level still requires continuous enhancement, support and upgrading [46]. The conventional solution which is commonly applied is to adjust the OLTC feature of the distribution transformer to meet the voltage requirement to maintain voltage profile. Nevertheless, the possibilities for maintaining the voltage profile within acceptable limits can be done by exchanging reactive power and curtailing active power by installed PVs along the feeder.

To examine the residential three-phase LV network with rooftop PVs, this chapter will discuss the model of the LV network and rooftop PVs. In addition, this chapter also will discuss the approaches mentioned earlier and their implementation in the modelled network.

2.1 Modelling LV Network

In order to model the residential three-phase LV test network, various technical data must be taken into account and must meet the current network topology standards [46]. As the test network has been determined, the next step is conducting the load flow analysis for the network.

2.1.1 Network under Consideration

The selected test network is an 11 kV three-phase medium voltage feeder supplying a 415 V three-phase four-wire low voltage residential feeder. This network topology is common in many countries including Australia [35]. It is to be noted that although this type of LV distribution networks is common in Australia and many parts of Asia, Europe and Africa, it is not the common practice in northern American countries. The following various technical data must be taken into account. The network is shown schematically in Figure 2.1.

The distribution transformer is a three-phase 150 kVA DYn type transformer with common multiple earth neutral (CMEN) system [47]. All residential loads are assumed as single-phase type, distributed equally among the three phases of the network. The network conductors are assumed to be of bare All Aluminium Conductor (AAC) overhead type, distributed over cross-arms with vertical configurations over the poles. Assuming the after diversity maximum demand (ADMD) of 4.7 kVA for each single house and length of 400 meters for the lines, the transformer ratings and conductor cross sections are selected based on engineering judgments, using the Australian Standards [9].

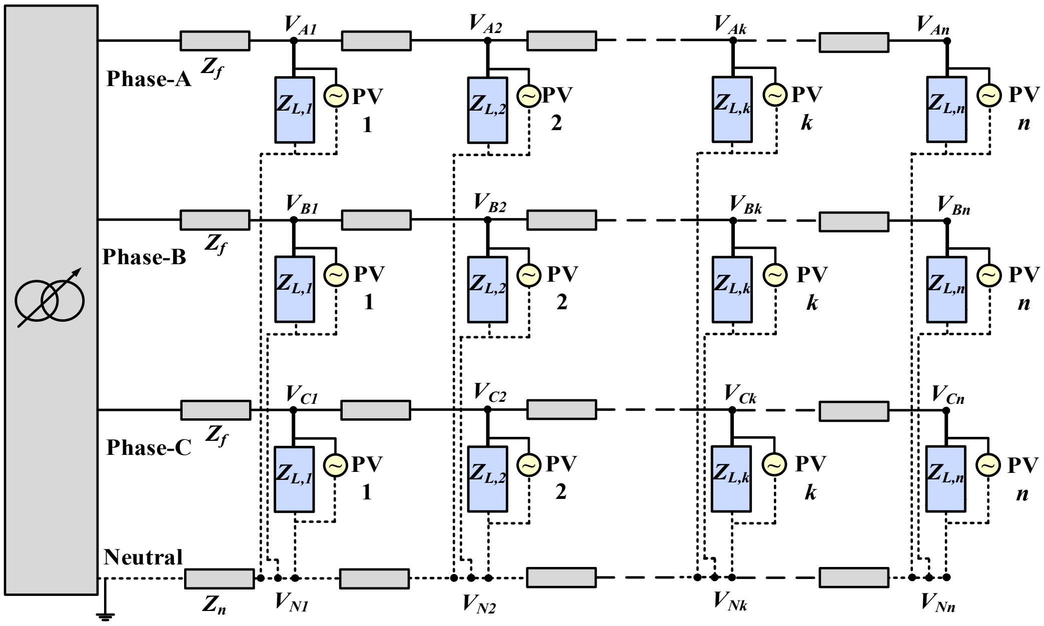

Figure 2.1. The simulated three-phase unbalanced residential LV network with single-phase rooftop PVs.

All residential loads are assumed as constant power type for simplicity. It is to be noted that although the number of houses is the same for all phases, their instantaneous power consumption is different which makes the system unbalanced. It is assumed that each house may have a rooftop PV system connection. However, the PVs may have different ratings which will further make the system unbalanced.

2.2.2 LV Load Flow Analysis

As commonly conducted, the flowchart of the load flow method must first be taken into account. This flowchart will describe every step involved in the development of load flow method. The flowchart can be seen in Figure 2.3.

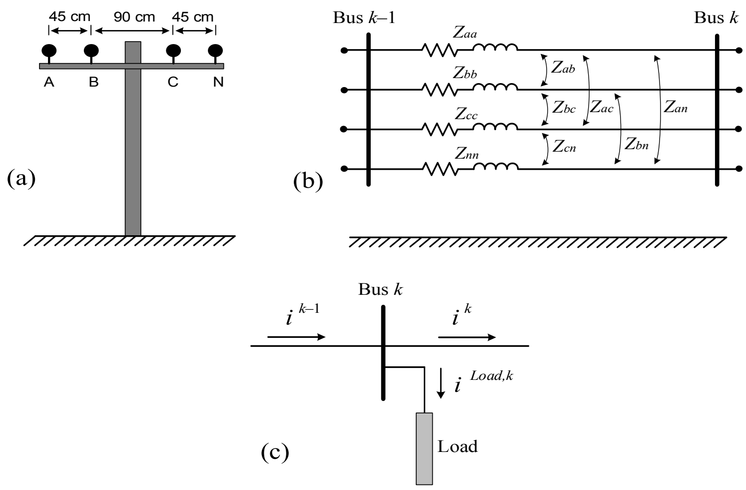

Figure 2.2. (a) LV feeder configuration, (b) Impedance equivalent of a line segment between two buses, (c) PQ bus model.

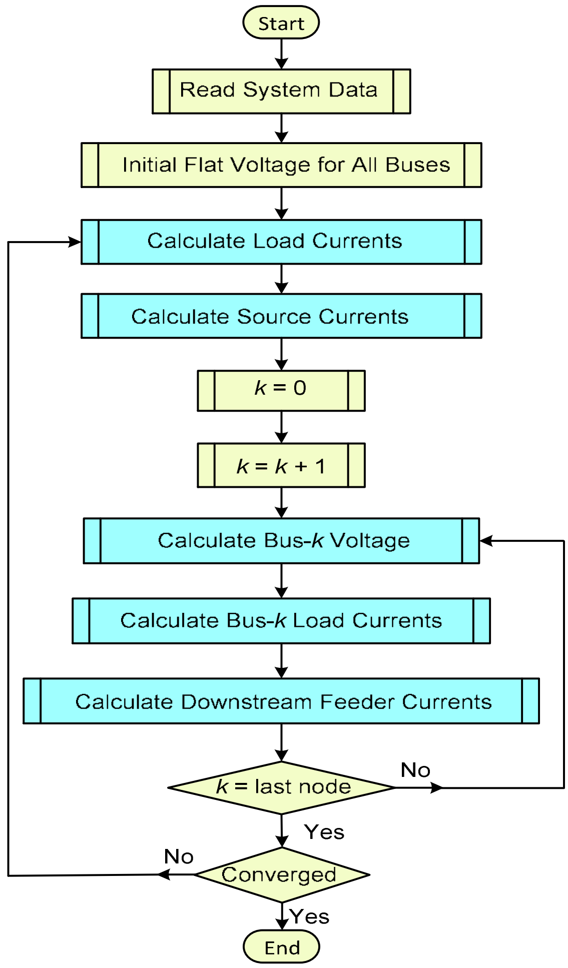

Figure 2.3. Flowchart of developed unbalanced load flow analysis.

Due to mitigate the voltage rise problem on the chosen LV network, successive load flow calculations are executed using MATLAB. An unbalanced sweep forward-backward load flow method is developed and used for the analysis of the three-phase four-wire radial LV network under consideration. The load flow calculates the bus voltages along the feeder.

First, in the load flow, the modified Carson's equations [48] are utilized for calculation of self and mutual impedance of the conductors in 50 Hz system as

$$Z_{ii} = r_i + 0.04934 + j0.062832 \left[7.10988 - \mathrm{Ln}\left(GMR_i\right)\right] \quad (2.1)$$

$$Z_{ij} = 0.04934 + j0.062832 \left[7.10988 - \mathrm{Ln}\left(D_{ij}\right)\right] \quad (2.2)$$

where i and j are the phase conductor (i.e., A, B, C or Neutral), Z_{ii} is the self-impedance of conductor i (in Ω/km), Z_{ij} is the mutual impedance between two conductors i and j (in Ω/km), r_i is the ac resistance of conductor i (in Ω/km), GMR_i is the geometric mean radius of conductor i (in cm) and D_{ij} is the distance between conductors i and j (in cm). Hence, the non-transposed characteristics of the conductors, image conductors below ground and network configuration are considered in the studies. Figure 2.2(a) shows the considered line configuration in this study [48].

The three-phase four-wire line segment between two adjacent buses of $k - 1$ and k is also shown in Figure 2.2(b). From (1) and (2), the equivalent impedance for the line section shown in Figure 2.2(b) is expressed as:

$$[\mathbf{Z}_{abcn}] = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} & Z_{an} \\ Z_{ba} & Z_{bb} & Z_{bc} & Z_{bn} \\ Z_{ca} & Z_{cb} & Z_{cc} & Z_{cn} \\ Z_{na} & Z_{nb} & Z_{nc} & Z_{nn} \end{bmatrix} \quad (2.3)$$

Assuming the transformer has delta/wye-grounded configuration and using Kron reduction, (3) can be rewritten as

$$[\mathbf{Z}_{abc}] = \begin{bmatrix} Z_{aa-n} & Z_{ab-n} & Z_{ac-n} \\ Z_{ba-n} & Z_{bb-n} & Z_{bc-n} \\ Z_{ca-n} & Z_{cb-n} & Z_{cc-n} \end{bmatrix} \quad (2.4)$$

All calculations are carried out in per unit (pu). Starting with a set of initial values (e.g. a flat voltage set), the load currents are calculated as

$$[\mathbf{I}_{abc}^{Load,k}] = \left([\mathbf{P}_{abc}^{Load,k}] - j[\mathbf{Q}_{abc}^{Load,k}]\right) / \operatorname{conj}\left([\mathbf{V}_{abc}^{k}]\right) \quad (2.5)$$

where $[\mathbf{I}_{abc}{}^{Load,k}]$ is a vector of three-phase load currents connected to bus k, $[\mathbf{V}_{abc}{}^{k}]$ is a vector of three-phase voltages of bus k, $[\mathbf{P}_{abc}{}^{Load,k}]$ and $[\mathbf{Q}_{abc}{}^{Load,k}]$ are respectively the vectors of three-phase active and reactive power consumption of residential load connected to bus k and conj() represents the conjugate operator.

The sum of the all load currents will flow from the first bus (i.e. transformer secondary side) to the second bus. Therefore, as shown in Figure 2.2(c), the current between two adjacent buses is

$$[\mathbf{I}_{abc}^{k}] = [\mathbf{I}_{abc}^{k-1}] - [\mathbf{I}_{abc}^{Load,k}] \quad (2.6)$$

Hence, the voltage of bus k can be calculated based on the voltage of bus $k-1$ in its upstream and the current passing between two buses as

$$[\mathbf{V}_{abc}^{k}] = [\mathbf{V}_{abc}^{k-1}] - [\mathbf{Z}_{abc}][\mathbf{I}_{abc}^{k}] \tag{2.7}$$

Once the voltage at bus k is calculated, the load current in that bus will be updated from (5) and then using (6) the current flowing from bus k to $k + 1$ in its downstream is updated.

Similar to the line segment, the equivalent impedance of the delta/wye-grounded distribution transformer between its primary and secondary buses is expressed as

$$[\mathbf{Z}_{abc}^{k}] = z_t \times \mathbf{I}_3 \tag{2.8}$$

where z_t is the phase impedance of the transformer and $\mathbf{I}_3$ is the identity matrix of 3×3. Now, the secondary-side voltage of the transformer is calculated from its primary-side voltage as [48]

$$[\mathbf{V}t_{abc}^{S}] = [\mathbf{A}][\mathbf{V}t_{abc}^{P}] - [\mathbf{Z}t_{abc}][\mathbf{I}_{abc}] \tag{2.9}$$

where $[\mathbf{V}t_{abc}{}^{P}]$ and $[\mathbf{V}t_{abc}{}^{S}]$ are respectively the primary and secondary-side phase voltages of the transformer and $[\mathbf{I}_{abc}]$ is a vector of three-phase current passing through the transformer and

$$[\mathbf{A}] = \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \tag{2.10}$$

2.2 Voltage Regulation Method

Rooftop PVs inject active power during the day while most household loads are at their minimal levels. Around noon, the output power of the PVs reaches their maximum level. This can result in active power flow in the opposite direction towards the grid, hence causing volt-age rise beyond acceptable levels at some buses. On the other hand, unequal distribution of rooftop PVs will result in different voltage rises in the three phases of the feeder.

Injecting reactive power by the PV inverters to the grid, curtailing the active power output of the PV inverters and utilizing OLTC transformers can be effective approaches for voltage amplitude control within the network. Recent studies have only considered three-phase PV systems [39]. However, the situation is very different when single-phase PVs are installed unequally at different phases and buses throughout the network and have different ratings. In this thesis, the combination of distributed reactive power support and active power curtailment by the inverters of the rooftop PVs, in addition to the OLTC of the LV transformer are considered to regulate the network voltage profile.

2.3 Voltage Adjustment Using OLTC Transformer

Voltage profile along the LV feeder should be kept within the recommended limits of 95% and 110% of the nominal voltage [35]. By utilizing a transformer with OLTC, the turns ratio of the transformer is adjustable. Figure 2.4 shows the schematic diagram of a transformer with OLTC. Assuming a constant primary voltage, the transformer’s secondary voltage can be increased or decreased such that the voltage all along the feeder is kept within acceptable limits.

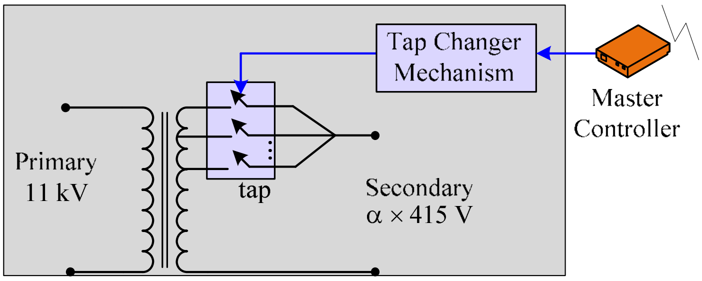

Figure 2.4. OLTC LV distribution transformer.

This method is based on the assumption that two three-phase voltage sensors are installed in the network, one set at the beginning of the feeder and another set at the end of the feeder. Both of these voltage sensors are assumed to have data communication capability such as WiFi or ZigBee to transfer the measured voltage to the master controller that is installed at the distribution transformer. These voltage sensors are shown in Figure 2.5.

First, the feeder end voltage is monitored with the help of the installed voltage sensors and this data is transferred to the master controller. Once the voltage at the feeder end reaches above the allowable limit, the master controller sends a proper command to the transformer tap changing system to select and activate a lower tap. Hence, the voltage all along the feeder reduces.

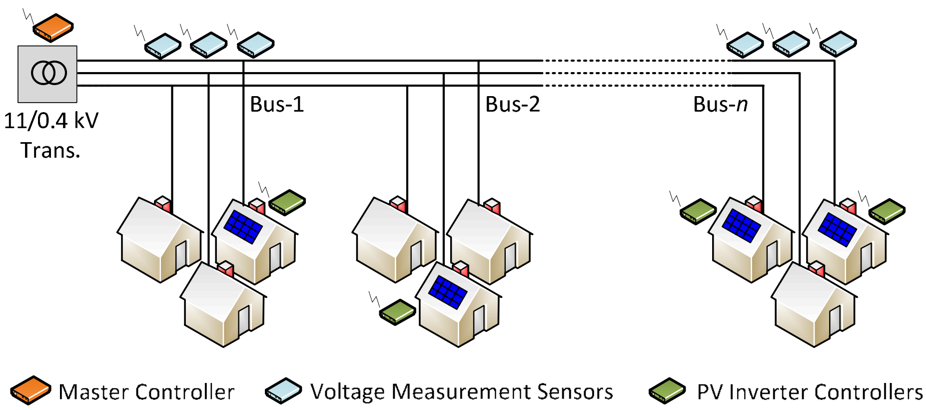

Figure 2.5. Schematic representation of the controllers in the network.

After this process, the feeder's beginning voltage is monitored with the help of the installed voltage sensor and its data is transferred to the master controller. This voltage should be kept above the minimum allowable limit. Then, if the voltage at the end of the feeder is still above the maximum allowable limit, the process will be repeated to reassure the voltage all along the feeder is within the acceptable limit. Hence, with the help of a transformer with OLTC, the secondary voltage can be reduced up to a minimum of 80%.

Due to the unbalance in the system, the three voltages may be different at the end of the feeder. In such cases, the master controller reduces the tap such that all three-phase voltages at the feeder end are limited below the maximum allowable limit.

It is to be noted that the OLTC does not operate instantaneously. The system allows a time delay of ΔT (in few minutes range) between two consequent operations. The flowchart of the method for adjusting the proper tap of the transformer is shown in Figure 2.6.

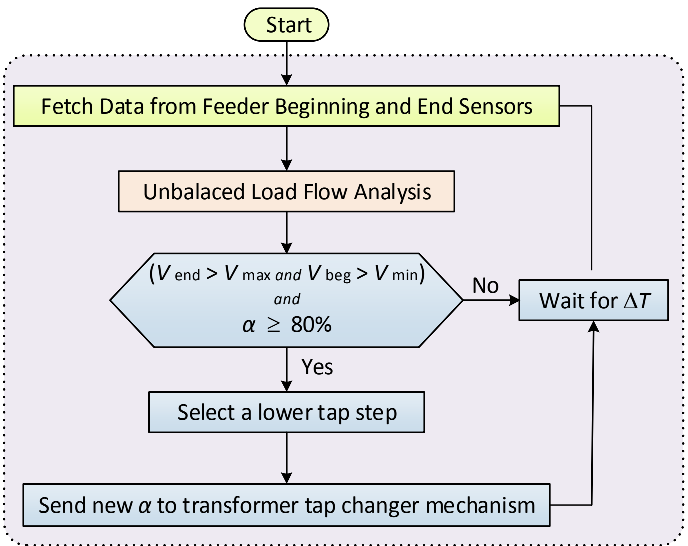

Figure 2.6. Flow chart of tap changer control algorithm.

2.4 Voltage Regulation by Reactive Power Support

Consider the LV feeder of Figure 2.1 with 10 buses where each bus may have single-phase PVs. Currently, based on IEEE recommended practice for utility interface of PV systems [9], the PV inverters operate in constant output power mode. Under such conditions, they only inject current with unity power factor and do not affect the voltage at their point of common couplings (PCCs). If the inverters are operated in voltage control mode, each PV inverter can correct its own PCC voltage to a desired value by injecting or absorbing the required amount of reactive power ($Q_{\mathrm{PV,ref}}$). To minimize PCC voltage error from its reference, each PV inverter needs to exchange reactive power with the feeder to keep the voltage of its output equal to the desired value. This can be achieved in a decentralized method using the droop control strategy as [26]

$$Q_{\mathrm{PV,ref}} = m(V_{\mathrm{PCC,ref}} - V_{\mathrm{PCC}}) \tag{2.11}$$

where $m > 0$ is the droop coefficient and will be assigned by the reactive power-voltage (Q-V) droop controller. The Q-V droop controller improves the dynamic oscillations between the reactive power and the voltage variation in the system. The droop control concept is demonstrated in Figure 7. It is to be noted that for rooftop PV inverters, the active power-frequency (P-F) droop controller will not be used since frequency variation is very small in the stiff grid-connected distribution networks. The selected $Q_{\mathrm{PV,ref}}$ in (11) must be within the inverter capacity as

$$-\sqrt{S_{\mathrm{PV,max}}^2 - P_{\mathrm{PV}}^2} \leq Q_{\mathrm{PV,ref}} \leq \sqrt{S_{\mathrm{PV,max}}^2 - P_{\mathrm{PV}}^2} \tag{2.12}$$

where $S_{\mathrm{PV,max}}$ is the maximum apparent power of the PV inverter and P_{PV} is the active power supplied by the PV at that time. If the selected (required) $Q_{\mathrm{PV,ref}}$ is beyond the inveter maximum injection or absorption capability, it will be limitted to the maximum limits.

The proposed algorithm in this paper will define and calculate $V_{\mathrm{PCC,ref}}$ based on the following conditions:

1- If a PV is available on all three phases of bus *i*, $V_{\mathrm{PCC,ref}}$ at this bus is equal to the average of the voltage magnitudes of the three phases:

$$V_{\mathrm{PCC,ref},i} = \frac{1}{3}(V_{\mathrm{A,i}} + V_{\mathrm{B,i}} + V_{\mathrm{C,i}}) \tag{2.13}$$

2- If PVs are available only on two phases of bus *i* (e.g. on phases "B" and "C"), $V_{\mathrm{PCC,ref}}$ at this bus is equal to the voltage magnitude of the third phase (e.g. phase "A").

3- If a PV is available only on one phase of bus *i* (e.g. on phase "A"), $V_{\mathrm{PCC,ref}}$ at bus *i* is equal to the average of the voltage magnitudes of the other two phases, i.e.

$$V_{\mathrm{PCC,ref},i} = \frac{1}{2}(V_{\mathrm{B,i}} + V_{\mathrm{C,i}}) \tag{2.14}$$

4- If no PV is available on any of the phases of bus *i*, then $V_{\mathrm{PCC,ref}}$ will not be defined for this bus as no PV can directly control the voltage at this bus. However, the voltage of this bus will be affected by changes in voltage at the other buses of the feeder.

Note that for each bus with rooftop PV, $V_{\mathrm{PCC,ref}}$ will be determined based on the data transmitted from the installed voltmeters at each phase to the rooftop PV controller throught the smart meters.

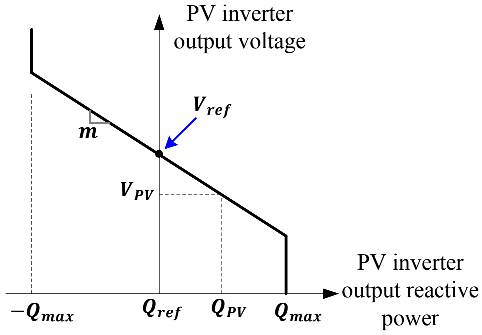

Figure 2.7. The proposed Q-V droop characteristic for rooftop PV inverters.

The flowchart of the method for regulating the voltage profile of the LV feeder with rooftop PVs is shown in Figure 2.8. In this flowchart, $Q_{\mathrm{PV,ref}}$ must have been selected within the inverter capacity as it formulated in (2.11).

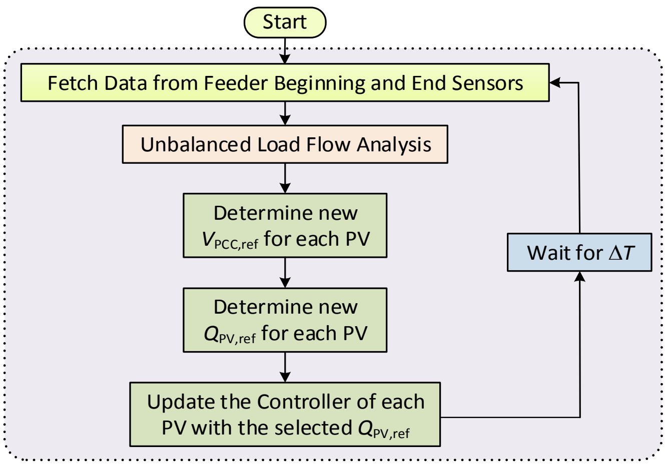

Figure 2.8. Flow chart of reactive power support algorithm.

2.5 Voltage Unbalance Reduction by Active Power Curtailment

Another effective approach to controling the voltage is curtailing the output active power of the rooftop PVs (P_{PV}) . In this method, the output active power of the PVs, dicatated by the maximum power point tracking (MPPT) algorithm (P_{MPPT}) will be deliberately reduced based on the error of the feeder voltage at a specific bus to minimize voltage unbalance in the feeder. To do this, the PV inverter active power output is conrolled as

$$P_{\mathrm{PV}} = P_{\mathrm{MPPT}} - n(V_{\mathrm{PCC,ref}} - V_{\mathrm{PCC}}) \tag{2.15}$$

where n is the curtailment coefficient that needs to be defined to minimize the difference between the magnitudes of all three phase voltages.

The flowchart of the method for reducing voltage unbalance of the LV feeder with rooftop PVs is shown in Figure 2.9. It shows that as P_{PV} set as in (2.15), the voltage unbalance can possibly be reduced.

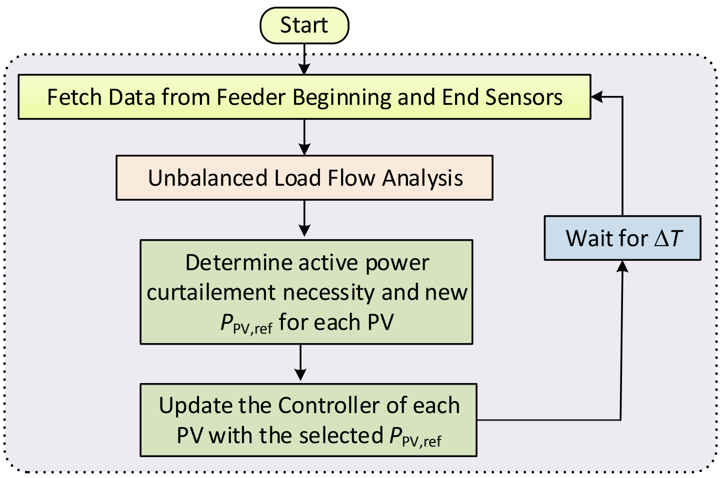

Figure 2.9. Flow chart of active power curtailment algorithm.

The above-mentioned voltage requlation methods using OLTC voltage reduction, reactive power support and active power curtailment are combined together to achieve better results.

2.6 PV Inverter Communication Concept

The Ethernet communication based on server/client architecture was used to exchange information [1]. Each PV Inverter will send its voltage information to the control server which will calculate and send back to the inverters the optimal reactive power reference using the proposed methods which have been previously discussed. Each PV system in the network of Figure 2.1 has the configuration presented in Figure 2.10.

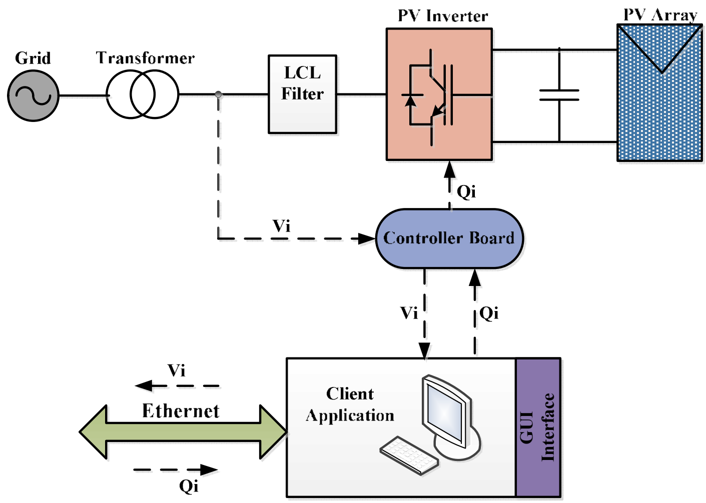

Figure 2.10. Configuration of PV inverters communication in the proposed LV network.

Using this concept, it will be possible to transmit the voltage information at the PCCs of the PV systems and to receive reactive power reference values for the PV inverters using Ethernet.

CHAPTER 3

VOLTAGE ADJUSTMENT OF UNBALANCED LV FEEDER WITH ROOFTOP PVs USING OLTC TRANSFORMER

3.1 Recent Studies

As penetration levels of rooftop PVs remain to increase in LV residential feeders, the utility companies are discovering that conventional strategies for regulating the voltage profile along the feeders are becoming less effective since PVs effect the bidirectional variations in real power flow into the distribution system [33]. Traditionally, utilities use traditional centralized voltage regulators such as load-tap-changing (LTC), SVR and capacitors for reactive power and voltage control in distribution systems. LTCs, located in distribution substations, are the most common devices to regulate voltage [49]. The application of OLTC feature of transformer was conventionally limited to HV/HV or HV/MV transformers, though the small, low-cost distribution transformers demerit the cost and density of OLTC and were typically provided with off-circuit taps [50]. This arrangement allowed the tap positions to be adjusted to suit the network conditions, usually when the transformer was initially placed into service. However, the facility which allowed the adjustments has to be made subsequently, whenever possible changes to the network loading have necessitated [51]. The conventional OLTC control system measures the voltage and load current, estimates the voltage at a remote point and triggers the tap-changer when the expected voltage is out of limits [50].

During daylight, as the residential load demand is decreased, PVs generate power at its highest capacity. The generated power flows in the reverse direction from the feeder to the distribution transformer. It can cause the voltage at the end of the feeder to rise with respect to the distribution transformer connection point. Ideally, it can cause over voltages if the transformer tap setting is too high. On the other hand, as the evening load peak rises and PVs generate less power, the power flows along the feeder towards the feeder end point, and the end point voltage drops with respect to the distribution transformer connection point. This can cause an under voltage if the transformer tap setting is too low. There is also a condition when the PV ratings are at their maximum values, this is the scenario when nearly every household within the LV network has installed rooftop PV, as expected there will be voltage rise issues in the network. For that reason, it is important to deploy transformer with OLTC to step down the voltage at the substation so that at the end of feeder voltage still maintain within the allowable limits.

Characteristically, one single tap setting will not fulfil the wide range of load conditions. Therefore, a prompt capability to correct voltage profile variations is required, because moving clouds over the PV arrays of the PV systems can cause rapid changes in the PV injected power within only a few seconds, with corresponding feeder voltage fluctuations [52].

Several studies have been conducted in order to control a feeder voltage profile in the existence of significant PVs penetration. The common approach is to facilitate reactive power generation from the PV inverter units, to avoid significant voltage rises [53]. Furthermore, reference [54-56] studied the impact of high residential PVs penetration on voltage profiles, considering the effects of feeder impedances, level of PVs penetration, transformer short circuit resistance, and protection and operation of the feeder. Reference [49] presented a strategy to vary this position on a cycle by cycle basis by incorporating an electronic tap changer into the LV feeder supply transformer. It also stated that on-line tap changers must have the ability to maintain a continuous current path during tap changing without creating a transient short circuit between the taps.

The tap of the OLTC transformer reduction is observed. The range of the transformer ratio in percent and the number of the steps depend on the design of the transformer and the OLTC. The voltage between the taps is the step voltage, and it normally lies between 0.8% and 2.5% of the rated voltage of the transformer [19]. Furthermore, the width of the steps cannot be arbitrarily large as the change of the tap would be too obvious to the customers.

Through various studies which mentioned above, this chapter evaluate the voltage adjustment using OLTC transformer in unbalanced three-phase residential feeder, through several developed case studies in order to analyse the impacts of rooftop PVs at different penetration levels at an LV residential network on the performance of OLTC feature of the distribution transformers.

3.2 Case Studies under Consideration

In order to evaluate the performance of the voltage adjustment using OLTC transformer method which has been discussed in sub section 2.3, several case studies have been developed to demonstrate the voltage profile along the LV feeders due to the various penetration level of PVs. The studies under consideration involved PV with various output power rating. Details of the case studies under consideration are as follow:

- Case-1: Majority of the PVs are installed at the beginning buses of the feeder.
- Case-2: Majority of the PVs are installed at the middle and end buses of the feeder.
- Case-3: All houses connected to phase-A have rooftop single-phase rooftop PVs while only a small portion of the houses connected to phase-B and C have PVs.
- Case-4: All houses connected to phase-B have rooftop single-phase rooftop PVs while only a small portion of the houses connected to phase-A and C have PVs.
- Case-5: refer to Case-3, with the network voltage profiles are evaluated over a 24-hr period.

These considered cases have been developed to indicate that the adjustment of OLTC of the transformer is a proper method to improve voltage profile along the feeder in the unbalanced three-phase residential feeder.

3.2.1 Majority of installed PVs at the beginning buses of the feeder

The first developed study case for the LV residential network under consideration is majority of the installed PVs are located at the beginning of the feeder. This study for the rest of the thesis will consider as case-1. Table 3.1 described the PV inverter ratings (in kVA) and locations for single-phase rooftop PVs, for phase-A, B and C, considered in the simulation case-1.

Table 3.1. PV inverter ratings (in kVA) for single-phase rooftop PVs, considered in the simulation case-1.

Bus No.	1	2	3	4	5	6	7	8	9	10
Phase					Case-1					
A	3	3	3	3	3	0	0	0	0	0
B	3	3	3	3	3	0	0	0	0	0
C	3	3	3	3	3	0	0	0	0	0

For case-1, PVs are installed with the uniform ratings of 3kW and located from bus 1 to 5 along the feeder for phase-A, B and C. In this case, the adjustment of OLTC of the transformer expected to adjust the voltage profile along the feeder to acceptable limits.

3.2.2 Majority of installed PVs at the middle and end buses of the feeder.

The second developed case, which for the rest of the thesis has considered as case-2 is the majority of the PVs are installed at the middle and end buses of the feeder. Table 3.2 indicates the PV inverter ratings for single-phase rooftop PVs in the unbalanced three-phase voltage profile simulations.

Table 3.2. PV inverter ratings (in kVA) for single-phase rooftop PVs, considered in the simulation case-2.

Bus No.	1	2	3	4	5	6	7	8	9	10
Phase					Case-2					
A	0	0	0	0	0	3	3	3	3	3
B	0	0	0	0	0	3	3	3	3	3
C	0	0	0	0	0	3	3	3	3	3

In this case, PVs are installed with the same ratings 3kW and located from bus 6 to 10 along the feeder for phase-A, B and C. In addition, the adjustment of OLTC of the transformer also expected to adjust the voltage profile along the feeder to acceptable limits.

3.2.3 All houses of phase-A have rooftop single-phase rooftop PVs

The third developed case has a scenario whereas all houses which are connected to phase-A have rooftop PVs with the PV inverter ratings are varies from 2-5kW and spread randomly along the feeder for phase-A, B and C. For the rest of the thesis, this case has considered as case-3. Table 3.3 specifies the PV inverter rating and location along the feeder.

Table 3.3. PV inverter ratings (in kVA) for single-phase rooftop PVs, considered in the simulation case-3.

Bus No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Phase	**Case-3**									
A	3	4	5	2	3	5	4	5	3	5
B	0	0	2	0	0	4	0	0	4	0
C	0	3	0	0	2	5	0	3	0	5

In this case, PVs are installed in various ratings 3-4kW and located randomly along the feeder for phase-A, B and C. While, in phase-A, PVs are installed at all buses. In addition, the adjustment of OLTC of the transformer also expected to adjust the voltage profile along the feeder to acceptable limits.

3.2.4 Single-phase rooftop PVs Distributed Randomly at All Phase

The fourth developed case is considered as case-4. This case will show the ineffectiveness of the adjustment of OLTC of the transformer method to regulating voltage profile in all three phases due to unavailability of adequate number of PVs in all phases. Table 3.4 specifies the PV inverter rating and location along the feeder for phase-A, B and C.

Table 3.4. PV inverter ratings (in kVA) for single-phase rooftop PVs, considered in the simulation case-4.

Bus No.	1	2	3	4	5	6	7	8	9	10
Phase						Case-4				
A	0	0	1	0	0	1	0	0	1	0
B	0	2	0	0	2	0	0	2	0	0
C	3	0	0	3	0	0	3	0	0	0

In this case, PVs are installed with the various ratings from 1-3kW and located for phase-A, B and C randomly along the feeder. It can be seen that this method has limitation for the case where the number and ratings of PVs in each phase, particularly at low penetrations of rooftop PVs. Moreover, the method also has dependency on data communication system. In addition, the adjustment of OLTC of the transformer also expected to adjust the voltage profile along the feeder to acceptable limits.

3.2.5 Random Location of PVs for 30 Houses Network over a 24-hr Period

As 30 houses are in the network, now a case can be considered to be evaluated over a 24-hr period, and it will be considered as case-5. Particularly for Case-5, the sunlight availability is assumed between 6 am and 18 pm while the PVs generate their maximum output at 12 pm, considering the sun radiation in Perth, Australia [57]. To consider the clouds effect on the PV output power generation, a white noise signal is added to the output power of the PVs. Figure 3.1 illustrates the considered PV output power for the duration of this study. Since the PVs are located in a close geographic area (400m) the same PV output power characteristic is used for all considered PVs in the network.

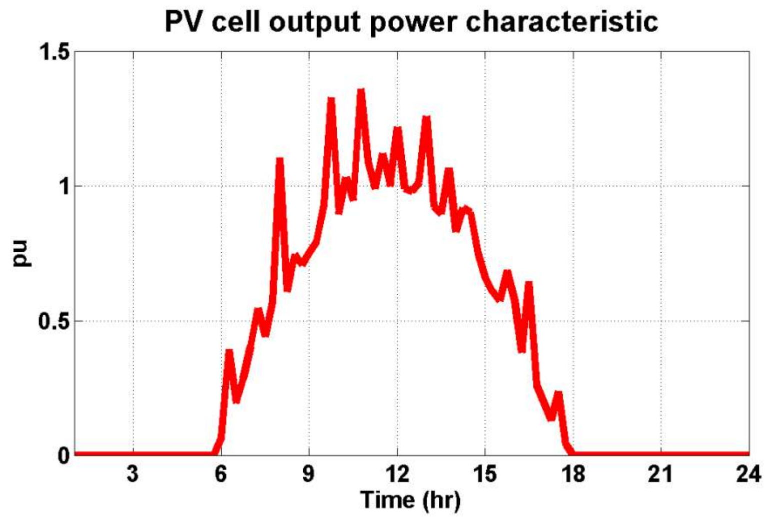

Figure 3.1. The considered PV output power for the duration of study.
Thirty-houses were considered for this case study including the PVs.

The load profile of the thirty-houses is illustrated in Figure 3.3. It can be seen that several houses experienced negative load profiles during 6am-6pm due to the PV power generation.

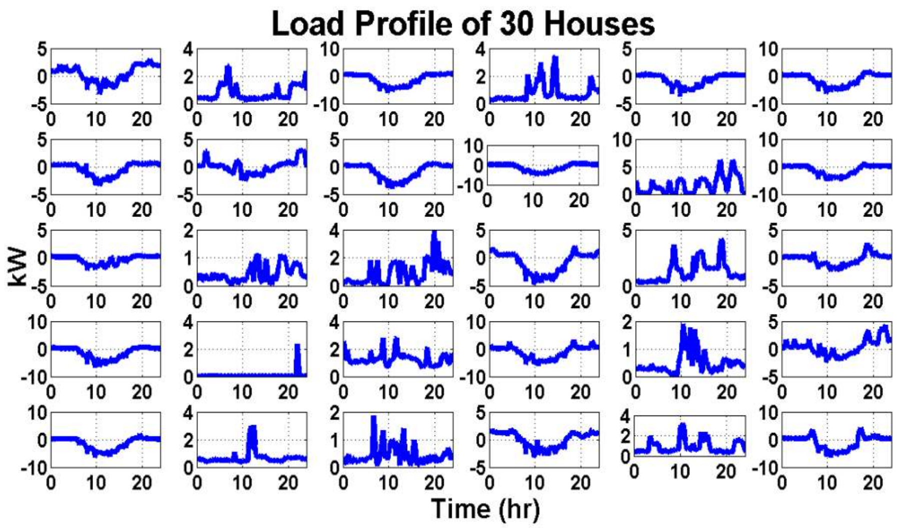

Figure 3.2. Load profile of 30 houses considered in the case study.

The tap position of the OLTC transformer is shown in Figure 3.4. It can be seen that during 9.00 am to 3.00 pm, the master controller has activated the OLTC mechanism to lower the tap to prevent non-standard voltage rise throughout the feeder.

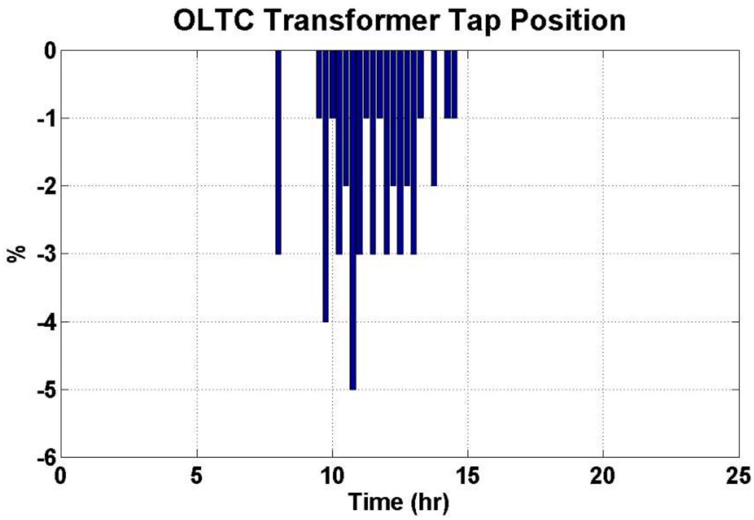

Figure 3.3. Tap position of the OLTC transformer in the case study.

3.3 Simulation Results of Developed Case Studies

As the cases developed, the four networks are used as the base cases to illustrate the effectiveness of the OLTC adjustment of the transformer method to regulate voltage profile. Figure 3.5, 3.6, 3.7 and 3.8 illustrate the voltage profile before and after improvement for all considered cases by applying voltage adjustment using OLTC of the transformer. Through these figures, OLTC transformer is successful in adjusting (lowering) the voltage profile along the feeder to acceptable limits of below 1.05 pu for case-2 (Figure 3.7b and 3.8b) but it cannot lead to voltage unbalance minimization (Figure 3.5b, 3.6b, 3.7b and 3.8b).

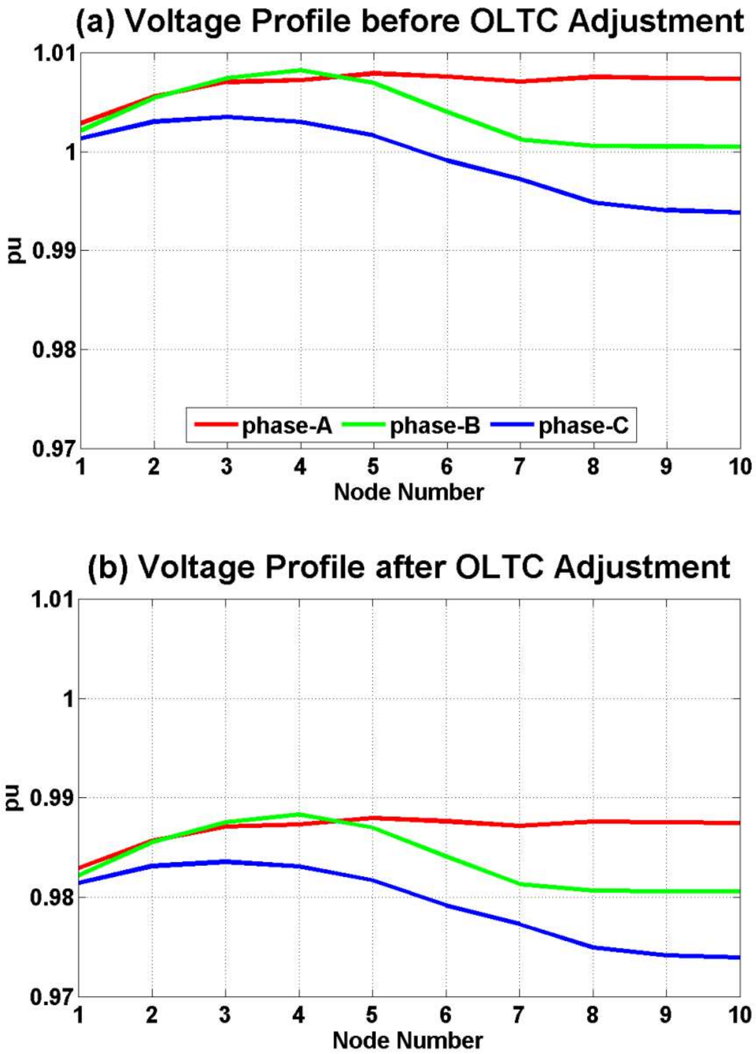

Figure 3.4. Three-phase voltage profile along the feeder for Case-1.

Figure 3.4(a) and (b) illustrate the voltage profiles before and after the adjustment of OLTC, respectively. For Case-1, whereas the rooftop PVs are located as described in Table 3.1, and installed with the uniformly ratings 3kW. It is expected that after applying the adjustment of OLTC feature of the transformer the voltage profiles along the feeder are within the acceptable limits as the transformer is lowering its tap. However, this method has less impact in reducing the unbalance voltage along the LV feeder.

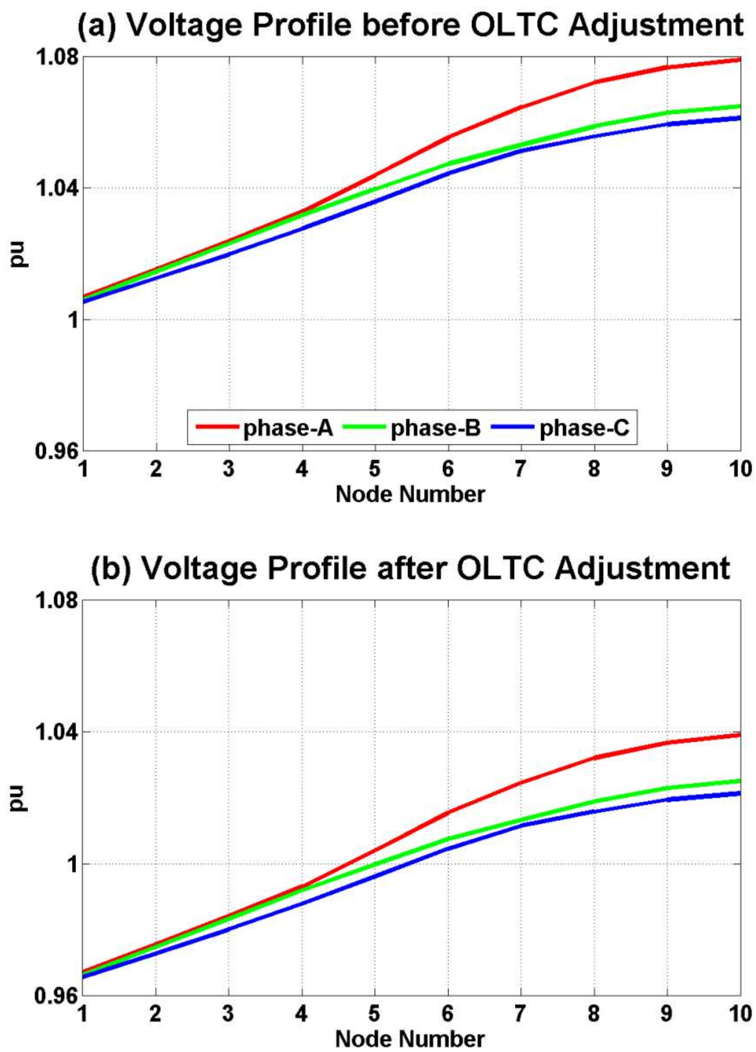

Figure 3.5. Three-phase voltage profile along the feeder for Case-2.

It can be seen that as majority of installed PVs at the middle and end buses of the feeder, the voltage profiles rise significantly beyond the acceptable limits as shown in Figure 3.5(a). The application of OLTC adjustment to regulate voltage profiles for Case-2 is illustrated in Figure 3.5(b). It can be seen that this method is successful only in lowering the voltage profiles into the acceptable limits.

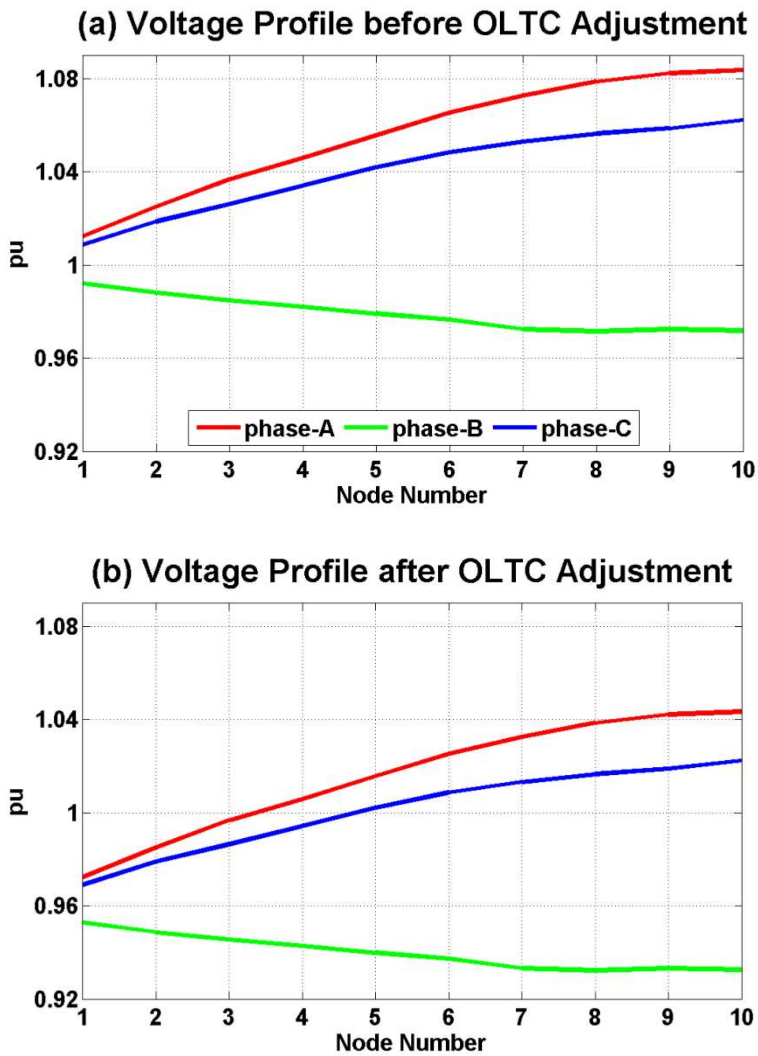

Figure 3.6. Three-phase voltage profile along the feeder for Case-3.

For Case-3, whereas all houses connected to phase-A have single-phase rooftop PVs, while only a small portion of the houses connected to phase-B and C have rooftop PVs. Once more it has proved that the OLTC adjustment method can be used only to regulate the voltage profiles in order to perform within the acceptable limits, as it presented as Figure 3.6(a). However, this method is unsuccessful in reducing the voltage unbalance along the LV feeder as it illustrated clearly in Figure 3.6(b).

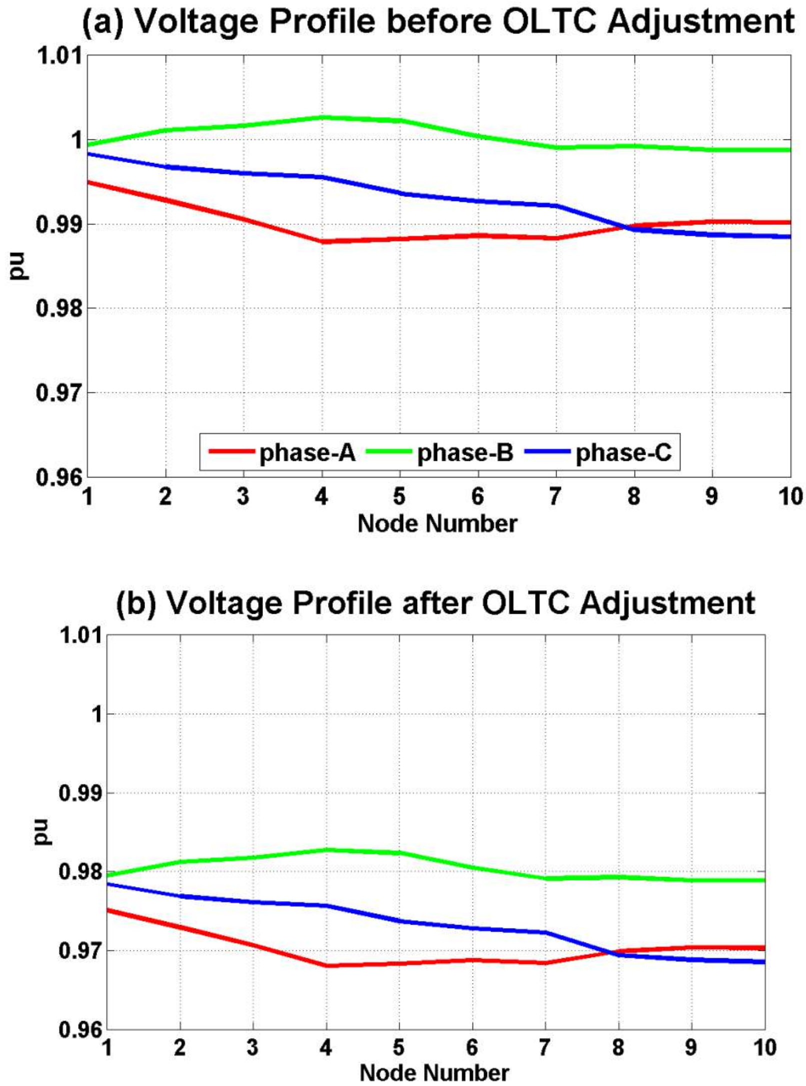

Figure 3.7. Three-phase voltage profile along the feeder for Case-4.

Figure 3.7(a) and (b) illustrate the three-phase voltage profiles along LV feeder before and after applying OLTC adjustment, respectively. As can be seen from these figures, although the voltage profiles are within the permissible range, the tap changer of the transformer is still lowering the voltage profiles as it set to adjust the secondary voltage of the transformer. The method is unsuccessfully reducing voltage unbalance.

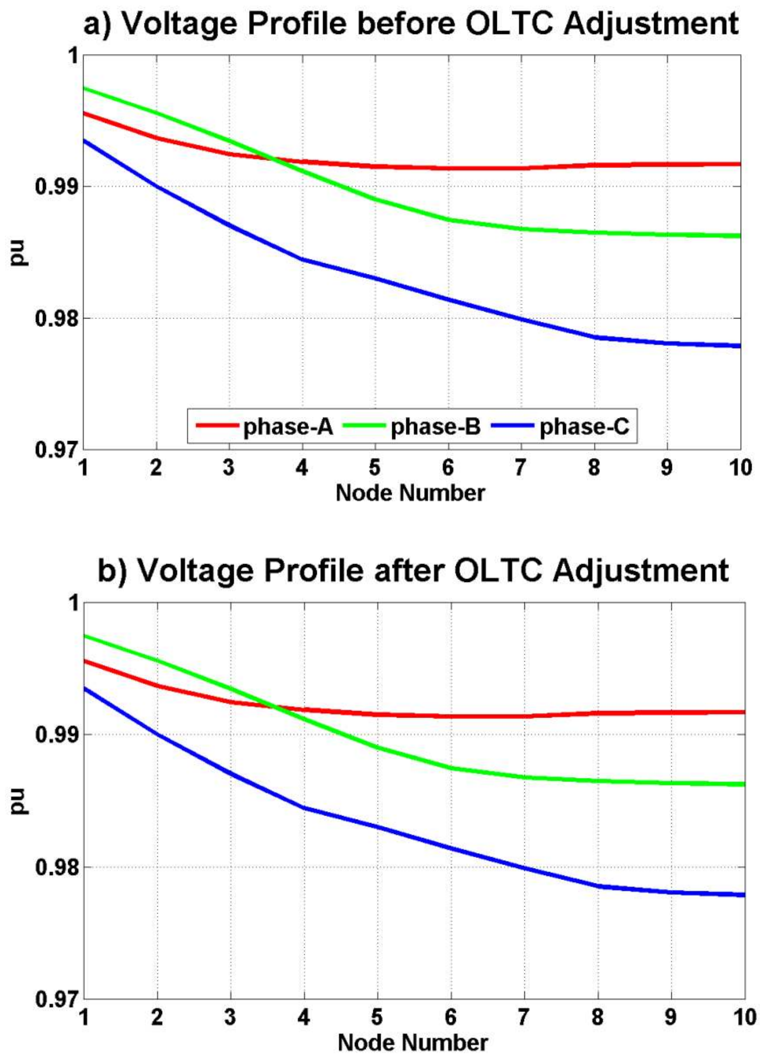

Figure 3.8. Three-phase voltage profile along the feeder for Case-5.

As case-5 was built over a 24-hr period, hence the best voltage profile which has been captured shown in Figure 3.8 was at 2.00 pm. In Figure 3.8b, it can be seen that the voltage profile after using OLTC of transformer shows less significant to voltage profiles show in previous cases.

The tap position of the OLTC transformer has successfully lowering the voltage profile that at the best captured time period, in this case at 2.00 pm. The master controller has activated the OLTC mechanisms to lower the tap of the transformer to prevent non-standard voltage rise throughout the feeder. A maximum of 5% tap reduction is observed in the considered case study, while in most cases the tap of the OLTC transformer has reduced only approximate 1-3%.

The simulation results demonstrate less effectiveness of the voltage adjustment of OLTC transformer method for the network with random load profiles, sun radiation and location/rating of the PVs over 24-hr periods. However, the proposed method will be successful and recommended for LV networks with high penetrations of single-phase rooftop PVs.

3.4 Summary

The approach consists of lowering the tap position of the OLTC distribution transformer if non-standard voltage rise is detected at the end of the feeder. It also defines proper reference voltages for the three phases of the network at each bus which will be used by the PV inverters. The method relies on the accessibility of smart meters at the buses along the LV feeder to transmit phase voltage measurements to the controllers of the PV inverters.

During daylight, as the residential load demand is decreased, PVs generate power at its highest capacity. By altering the tap position of the OLTC could effectively control the voltage rise problem. At the evening, the output from PV generators will intensely reduce, and house load demands will slowly increase, this could lead to voltage drop throughout the LV feeder. For this condition, the OLTC feature of transformer could hence increase the tap position to step up the feeder voltage.

A supplementary step for the above discussed method can be deliberated within an optimization problem to achieve enhanced results in voltage regulation with minimum effort on OLTC operation. Moreover, the effectiveness of the proposed method can be evaluated for different uncertain and random conditions of load profile and sun radiation with different ratings and locations of PVs using Monte Carlo analysis.

CHAPTER 4

REACTIVE POWER SUPPORT OF ROOFTOP PVs FOR VOLTAGE REGULATION OF UNBALANCED LV FEEDER

4.1 Recent Studies

The increasing installation of single-phase rooftop PVs in the residential network might change the direction of power flow and initiate voltage regulation problems. To overcome voltage regulation problems expected on the distribution circuits with high penetrations of PV generation, the allowable amount of the injection of reactive power can be exchanged to regulate the output voltage of PVs. Several recent studies have discussed the possibilities to exchange reactive power of PVs.

When the number of rooftop PVs on a distribution network is small, the impact is relatively small and the grid will not be affected. However, as the PV penetration on a distribution network grows the remaining impact of massive number of small rooftop PVs can reach an affected level of the power quality [47]. The alternate solution is by providing reactive power for voltage regulation on the individual, small-scale PV inverters by using excess PV inverter capacity to generate or consume reactive power. In one hand, the voltage regulation by injecting reactive power of PV inverters is not allowed by the current interconnection standard [35]. On the other hand, several approaches to enhancing the dispatch of reactive power for the purpose of voltage regulation and loss minimization that possibly would be modified to the present problem are including in [58-63]. Nevertheless, these works are rather specialized to optimal the location and/or control of few large sources of reactive power. In addition, in [4], it mitigates that by the utilization of rooftop PVs for exchanging reactive power due to balance their PCC voltage. Even though this method is very efficient in unbalance reduction of voltage profile, still it might take a few years for PV standards to be adopted for this strategy.

Concerning voltage rise problem in [24], a static voltage support is discussed. By providing control of reactive power injection/absorption, distributed PV based VSCs can contribute to network voltage as both dynamically and statically. Only static voltage support is considered regarding of voltage rise problem. On contrary, in [24], the two different reactive power reference trajectories are distributed to individual PV inverters in the framework of the minimization of total reactive power effort. In the other words, less reactive flow losses and maximization of voltage drop.

Recently, a trend research by utilizing the reactive power capability of smart inverters for voltage control in systems with large penetration of PV generation is developing [49]. Reactive power capability of an inverter-based PV generation is limited by the current carrying capacity of semiconductor switches [64]. As the real power injection is less than the rating of power inverter, remaining capacity can be utilized for the reactive power supply or absorption. A coordination scheme is proportional solution to address the issue of voltage regulation in case of different system operation and PV generation circumstances [49].

The sensitivity analysis has been preferred to be proposed in several studies regarding regulating voltage profile using reactive power support. Reference [62] studied that the sensitivity analysis shows that the same amount of reactive power becomes more effective for grid voltage support if the PV inverter is located at the end of a feeder. It also combines two droop functions that are inherited from the standard *cos* ϕ(P) and Q(U) strategies to prevent unnecessary reactive power absorption from the grid within the acceptable voltage limit or to increase reactive power contribution from the inverters that are closest to the transformer during grid overvoltage condition.

On the other hand, reference [15] studies that in an unbalanced network, asymmetrical spacing and non-transposition of line configurations can result in different voltage drops for each phase would cause voltage problems after a decline in PV generation, such as an extremely low voltage magnitude of a certain phase and an unacceptable voltage imbalance level at a remote bus. However, the problem has been overcome by implementing a method of analysing voltage variation sensitivity due to PV power fluctuations in an unbalanced network, or in other words, unbalanced line configuration and phase loading levels.

Another study which has been conducted in [1] discussed an improved Q(U) method was implemented due to minimize the reactive power consumption of the distribution system (DS) using the communication protocol IEC 61850. The Ethernet communication based on server/client architecture was used to exchange information. Although the communication concept will not discuss any further in this thesis, but it cannot be neglected that the coordination of PV inverters along the LV feeder must take the communication concept into account.

This chapter will evaluate and analyse the proposed voltage regulation by reactive power support approach. Several considered cases that have been simulated through the previous method (voltage adjustment using OLTC transformer) will be implemented using the reactive power support method.

4.2 Simulation Results of Developed Case Studies

In order to emphasize the voltage increase due to PV power generation, five case studies were considered. The voltage value at the slack bus before applying PV systems connection is chosen 1 pu. It has been estimated that the network experience voltage rise above the 3% of the allowable limit with the maximum rise at the end of the feeder. The method is determined by the existence of smart meters at the buses along the LV network to transmit the measured phase voltage to the controllers of the PV inverters.

The five considered case studies have the similar system configuration as they applied using the method of voltage adjustment using OLTC transformer, which has been discussed in Chapter 3. Figure 4.1, 4.2, 4.3, 4.4 and 4.5 illustrate the voltage profile before and after improvement for all considered cases by applying voltage regulation by reactive power support method.

In each of these figures, the voltage profiles before any improvements and after applying the proposed method are demonstrated. Through these figures, it is expected that the proposed method is able to regulate voltage profiles and reduce voltage unbalance.

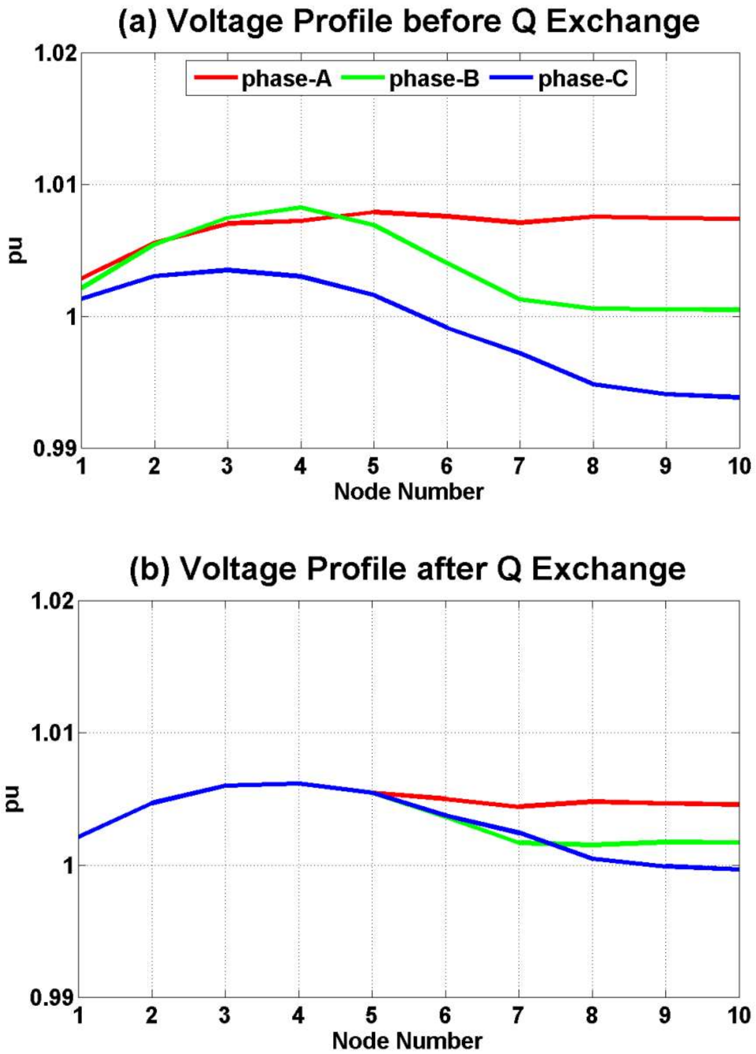

Figure 4.1. Three-phase voltage profile along the feeder for Case-1.

Figure 4.1(a) and (b) show the three-phase voltage profiles along LV feeder before and after applying the reactive power support method by PV inverters, respectively. For Case-1, whereas the majority of the single-phase rooftop PVs are installed at the beginning buses of the feeder, the method is successfully implemented in minimizing the voltage unbalance among the three-phases at the buses that the PVs are installed and have enough capacity to exchange reactive power with the feeder. Additionally, Table 4.1 indicates the voltage magnitude (pu) before and after the proposed method applied. Moreover, the reactive power injection (kVAR) of PV inverters along the feeder where the PVs are installed can be seen in Table 4.2.

Table 4.1 Voltage magnitude for Case-1

Bus / Phase	1	2	3	4	5	6	7	8	9	10
Voltage Profile (pu) before Q Exchange										
A	1.0029	1.0056	1.007	1.0073	1.0079	1.0076	1.0071	1.0076	1.0075	1.0074
B	1.0021	1.0055	1.0075	1.0083	1.0069	1.004	1.0013	1.0006	1.0005	1.0005
C	1.0014	1.0031	1.0035	1.003	1.0016	0.9991	0.9972	0.9948	0.9941	0.9938
Voltage Profile (pu) after Q Exchange										
Bus / Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
A	1.0021	1.0047	1.006	1.0062	1.0055	1.005	1.0044	1.0048	1.0047	1.0046
B	1.0021	1.0047	1.006	1.0062	1.0055	1.0036	1.0017	1.0015	1.0017	1.0017
C	1.0021	1.0047	1.006	1.0062	1.0055	1.0038	1.0024	1.0005	0.9999	0.9997

Table 4.2. Reactive power injection (kVAR) of installed PVs for Case-1

Bus / Phase	1	2	3	4	5	6	7	8	9	10
Reactive Power Injection (kVAR)										
A	0	-126.32	-78.653	611.324	12.9942	0	0	0	0	0
B	0	-649.51	-613.77	-655.65	-696.08	0	0	0	0	0
C	0	-432.18	-288.68	-377.66	-397.97	0	0	0	0	0

Table 4.3 Voltage magnitude for Case-2

Bus / Phase	1	2	3	4	5	6	7	8	9	10
Voltage Profile (pu) before Q Exchange										
A	1.0068	1.0152	1.0239	1.0329	1.0439	1.0555	1.0645	1.0721	1.0767	1.0791
B	1.006	1.0145	1.023	1.0317	1.0396	1.0473	1.0531	1.0587	1.0629	1.065
C	1.0055	1.0126	1.0199	1.0276	1.0359	1.0444	1.0514	1.0557	1.0593	1.0613
Voltage Profile (pu) after Q Exchange										
Bus / Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
A	1.007	1.0155	1.0243	1.0335	1.0446	1.0491	1.0563	1.0622	1.0663	1.0684
B	1.0059	1.0142	1.0226	1.0312	1.039	1.0491	1.0563	1.0622	1.0663	1.0684
C	1.0056	1.0128	1.0201	1.0279	1.0362	1.0491	1.0563	1.0622	1.0663	1.0684

Since the PVs capacity is 5kVA with the output power of 3kW, and they have sufficient power to exchange with the power along the LV feeder. As indicates in Table 4.2, the PV inverters inject/absorb reactive power along the feeder where the PVs are located. Similar behaviour occurs for Case-2, except in Case-2, the PVs are located at the middle and the end of the feeder.

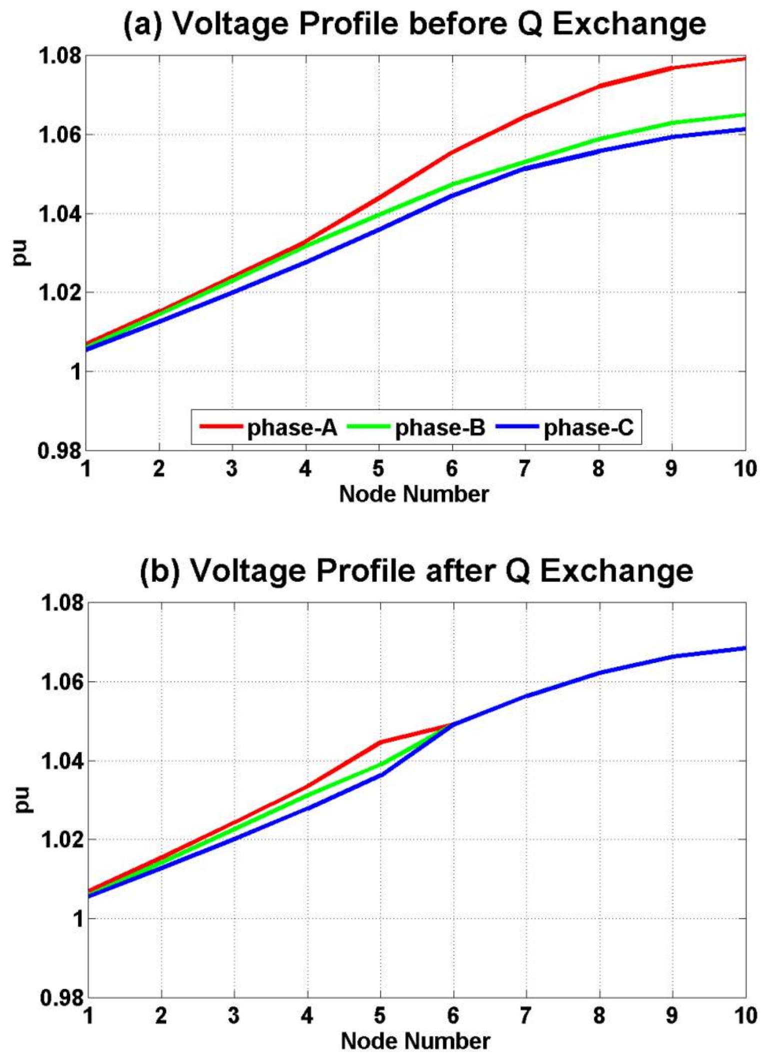

Figure 4.2. Three-phase voltage profile along the feeder for Case-2.

Table 4.4. Reactive power injection (kVAR) of installed PVs for Case-2

	Reactive Power Injection (kVAR)									
Bus / Phase	1	2	3	4	5	6	7	8	9	10
A	0	0	0	0	0	20.7023	295.765	15.9068	85.9838	0
B	0	0	0	0	0	36.641	973.273	175.515	31.3667	0
C	0	0	0	0	0	258.654	183.207	723.473	210.706	0

As for Case-2, Table 4.3 indicates the voltage magnitude (pu) before and after the proposed method applied and also the reactive power injection (kVAR) of PV inverters along the feeder where the PVs are installed can be seen in Table 4.4. The proposed method is successfully minimizing voltage rise and unbalance along the feeder which PVs are located. Through Figure 4.2(a), it can be seen that the voltage profiles rise beyond the acceptable limits. After applying the proposed method, it can be seen that the voltage profiles has been regulated and perform well within the acceptable limits as illustrates in Figure 4.2(b).

Table 4.5 Voltage magnitude for Case-3

	Voltage Profile (pu) before Q Exchange									
Bus / **Phase**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
A	1.0124	1.0251	1.0369	1.046	1.0559	1.0655	1.0728	1.0788	1.0824	1.0837
B	0.9922	0.9882	0.9849	0.9821	0.9792	0.9767	0.9725	0.9717	0.9725	0.9718
C	1.0089	1.0188	1.0263	1.0341	1.042	1.0485	1.0531	1.0565	1.0587	1.0623
	Voltage Profile (pu) after Q Exchange									
Bus / **Phase**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
A	1.0004	0.9867	1.0004	0.9969	0.9877	0.9985	0.9957	1.0024	0.9934	0.9948
B	0.9915	0.9867	0.9945	0.9912	0.9877	0.9966	0.992	0.9909	0.9934	0.9926
C	1.0092	0.9867	0.9945	1.0026	0.9877	0.9946	0.9994	0.9909	0.9934	0.9972

Table 4.6. Reactive power injection (kVAR) of installed PVs for Case-3

	Reactive Power Injection (kVAR)									
Bus / **Phase**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
A	0	-126.32	0	611.324	12.9942	0	37.611	0	-172.17	0
B	0	0	90.8131	0	0	36.641	0	0	31.3667	0
C	0	62.0049	0	0	96.216	0	0	723.473	0	0

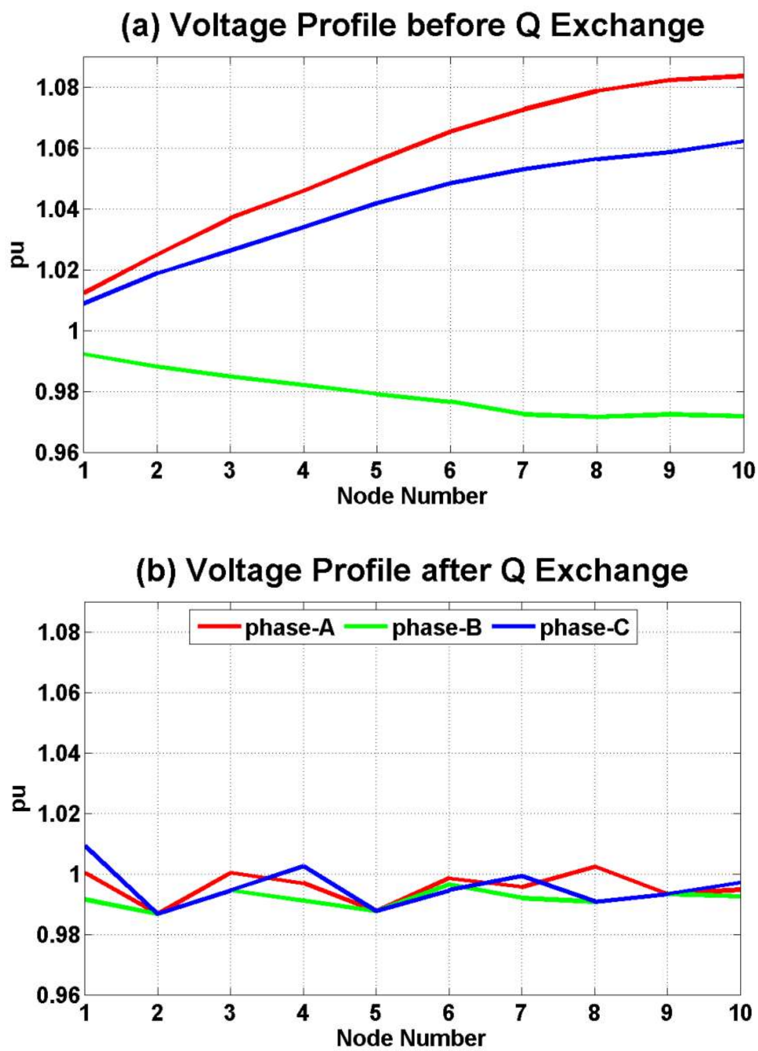

Figure 4.3. Three-phase voltage profile along the feeder for Case-3.

For Case-3, Table 4.5 and 4.6 indicate the voltage magnitude (pu) before and after the proposed method applied and the reactive power injection (kVAR) of PV inverters along the feeder, respectively. While Figure 4.3(a) and (b) indicate the three-phase voltage profiles along the feeder before and after applying the propose method, respectively. This method was performing Case-3, whereas all houses connected to phase-A have single-phase rooftop PVs while only a small portion of the houses connected to phase-B and C have PVs mounted on their rooftops. The significant impact of the proposed method can be seen through

Figure 4.3(b). The voltage rise and unbalanced along the feeder are successfully minimized.

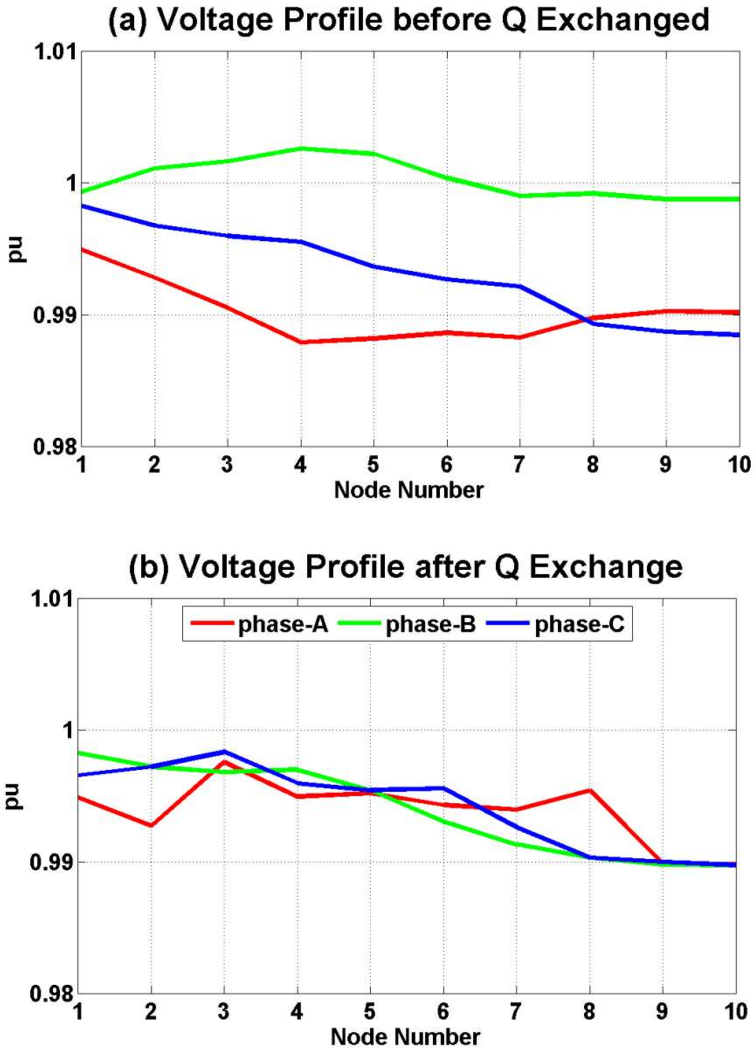

Figure 4.4. Three-phase voltage profile along the feeder for Case-4.

Case-4, whereas single-phase rooftop PVs distributed randomly at all phase and PVs location can be seen in Table 3.4. Through this case study, though the voltage profiles are within the acceptable limits, but the voltage unbalance occurs as PVs distribute randomly along the feeder. It can be seen in Figure 4.4(a). While, in Figure 4.4(b), as the proposed method is applied, the voltage unbalance can be reduced. Table 4.7 indicates the voltage magnitude (pu) before and after the proposed method applied. In addition, the reactive power injection (kVAR) of PV inverters along the feeder where the PVs are installed can be seen in Table 4.8.

Table 4.7 Voltage magnitude for Case-4

	Voltage Profile (pu) before Q Exchange									
Bus / Phase	1	2	3	4	5	6	7	8	9	10
A	0.9949	0.9928	0.9905	0.9879	0.9882	0.9886	0.9883	0.9898	0.9903	0.9902
B	0.9994	1.0011	1.0016	1.0026	1.0022	1.0004	0.999	0.9992	0.9988	0.9988
C	0.9983	0.9967	0.996	0.9955	0.9936	0.9927	0.9922	0.9893	0.9887	0.9885
	Voltage Profile (pu) after Q Exchange									
Bus / Phase	1	2	3	4	5	6	7	8	9	10
A	0.9949	0.9927	0.9976	0.9949	0.9952	0.9943	0.994	0.9954	0.9899	0.9898
B	0.9982	0.9972	0.9968	0.997	0.9954	0.9931	0.9913	0.9903	0.9898	0.9898
C	0.9966	0.9972	0.9983	0.996	0.9954	0.9956	0.9926	0.9903	0.99	0.9897

Table 4.8. Reactive power injection (kVAR) of installed PVs for Case-4

	Reactive Power Injection (kVAR)									
Bus / Phase	1	2	3	4	5	6	7	8	9	10
A	0	0	179.501	0	0	20.7023	0	0	85.9838	0
B	0	55.072	0	0	8.4993	0	0	175.515	0	0
C	0	0	0	-377.66	0	0	-310.98	0	0	0

Through these figures, it can be seen that reactive power support of PV inverters is successful in minimizing the voltage unbalance among the three-phases (Fig. 4.1b, 4.2b, 4.3b, 4.4b and 4.5b) at the buses that the PVs are installed and have enough capacity to exchange reactive power with the feeder. Besides, for case-5 whereas the captured voltage profiles for 24-hrs period was at 2.00 pm, it shows that the voltage profile after applying the reactive power exchange method indicates the significant improvement of voltage profiles.

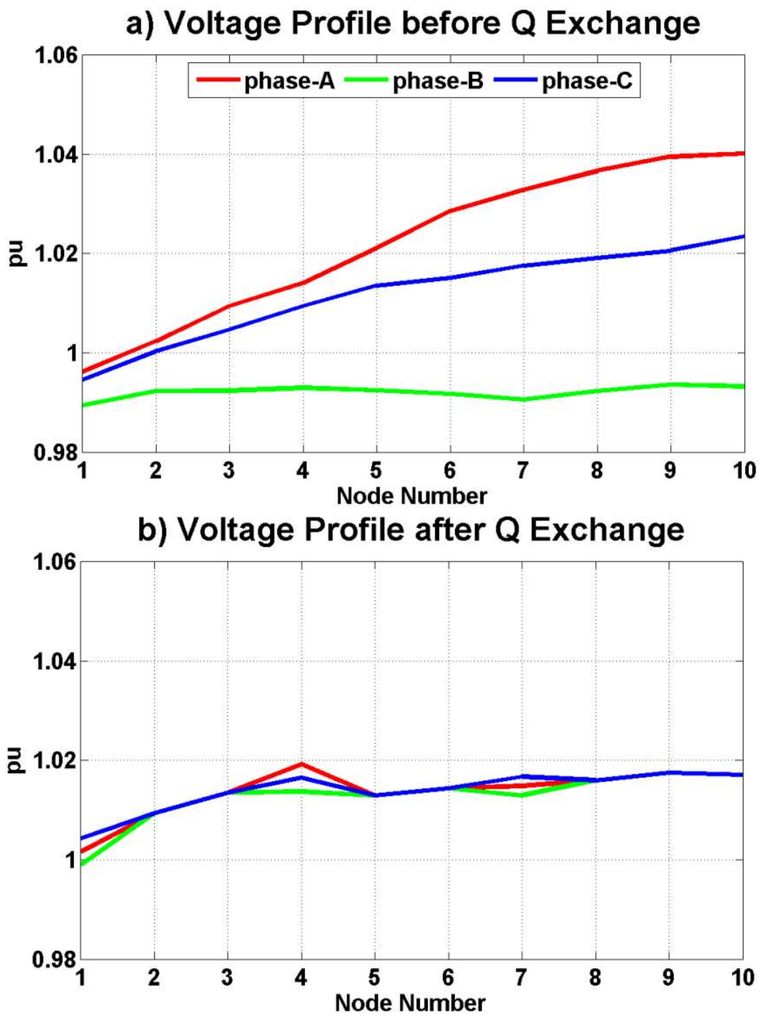

Figure 4.5. Three-phase voltage profile along the feeder for Case-5.

Table 4.9 Voltage magnitude for Case-5

	Voltage Profile (pu) before Q Exchange									
Bus / Phase	1	2	3	4	5	6	7	8	9	10
A	1.0004	1.0107	1.0219	1.0303	1.0396	1.0489	1.0539	1.0581	1.0615	1.0622
B	0.993	0.9968	0.9978	0.9993	1.0005	1.0018	1.0029	1.0052	1.0066	1.0062
C	0.9939	0.9999	1.0042	1.0086	1.0121	1.0124	1.0154	1.0179	1.0198	1.0233
	Voltage Profile (pu) after Q Exchange									
Bus / Phase	1	2	3	4	5	6	7	8	9	10
A	1.0022	1.0093	1.0132	1.0192	1.0134	1.0151	1.0162	1.0141	1.0153	1.015
B	1.0004	1.0093	1.0132	1.0134	1.0134	1.0151	1.0148	1.0141	1.0153	1.015
C	1.004	1.0093	1.0132	1.0163	1.0134	1.0151	1.0175	1.0141	1.0153	1.015

Table 4.10. Reactive power injection (kVAR) of installed PVs for Case-5

	Reactive Power Injection (kVAR)									
Bus / Phase	1	2	3	4	5	6	7	8	9	10
A	0	0	30.9883	0	324.426	90.0036	45.4856	241.718	274.027	0
B	0	320.628	41.5897	0	0	106.339	0	55.5167	7.561	0
C	0	276.377	0	265.026	89.3916	0	0	411.437	0	0

Overall, the simulation results determine the effectiveness of the application of the voltage regulation by reactive power support method. Furthermore, the proposed method will be successful and recommended for LV networks with high penetrations of single-phase rooftop PVs.

4.3 Limitation of the Voltage Regulation by Reactive Power Support Method

Even though the simulation results demonstrate that the proposed voltage regulation method is successful in reducing the voltage rise and unbalance in the LV network, this method highly relies on the number of PVs and their ratings in each phase. One of the limitations of the proposed method is when massive amount of the PVs are installed only at one phase then it would be failed to regulating the voltage profile in all three phases due to unavailability of adequate number of PVs in all phases. Another limitation of the method is when the PV inverters do not have a minimum of 10-20% higher rating compared to rated active power which is generated by the solar cells.

A case was considered with the network of Figure 1 in which ten single-phase PVs are installed at all buses of only one phase (in this case phase-B). Table 4.11 describes the PV inverter rating and location along the feeder for phase-A, B and C.

Table 4.11. PV inverter ratings (in kVA) for single-phase rooftop PVs, considered in the simulation of failure of the proposed voltage regulation method.

Bus No.	1	2	3	4	5	6	7	8	9	10
Phase	Case of failure of the proposed voltage regulation method									
A	0	0	2	0	0	2	0	0	2	0
B	2	2	2	2	2	2	2	2	2	2
C	0	0	2	0	0	2	0	0	2	0

Table 4.12. Voltage magnitude for failure case

	Voltage Profile (pu) before Q Exchange									
Bus	1	2	3	4	5	6	7	8	9	10
Phase										
A	1.0033	1.0068	1.01	1.0126	1.0151	1.0173	1.0189	1.0203	1.0212	1.0216
B	1.004	1.0091	1.0135	1.0173	1.0206	1.0231	1.0257	1.0277	1.029	1.0298
C	0.994	0.991	0.9891	0.9867	0.9848	0.9834	0.9814	0.98	0.9798	0.9791
	Voltage Profile (pu) after Q Exchange									
Bus	1	2	3	4	5	6	7	8	9	10
Phase										
A	1.001	1.0026	1.004	1.0052	1.0064	1.0075	1.0083	1.0091	1.0095	1.0097
B	1.0002	1.0022	1.0039	1.0053	1.0064	1.0073	1.0084	1.0094	1.0101	1.0104
C	0.9943	0.9916	0.9898	0.9878	0.9861	0.9846	0.983	0.9816	0.9813	0.9808

Table 4.13. Reactive power injection (kVAR) of installed PVs for failure case

	Reactive Power Injection (kVAR)									
Bus	1	2	3	4	5	6	7	8	9	10
Phase										
A	0	0	138.854	0	0	106.585	0	0	122.396	0
B	0	762.184	723.069	712.003	727.394	428.446	633.981	780.767	767.877	0
C	0	0	106.078	0	0	223.739	0	0	142.554	0

Figure 4.6 illustrates the voltage profiles along the feeder before and after implemented the reactive power exchange method. The method was unsuccessful to regulate the voltage profiles since there was insufficient reactive power to exchange as only at one phase (phase-B) PVs are located at all bus along the feeder, while less PVs are randomly located for other two phases (phase-A and C). Table 4.12 and 4.13 indicate the voltage magnitude in p.u. and the reactive power (kVAR) that been utilized by PV inverters for every bus along the feeder, respectively.

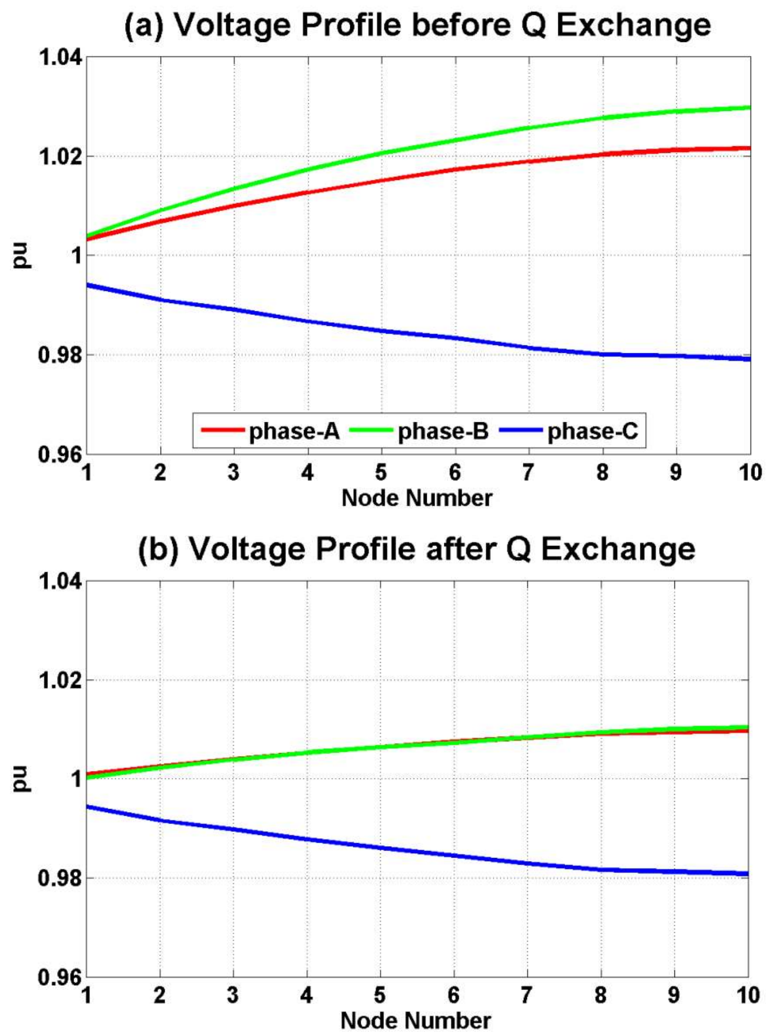

Figure 4.6. Three-phase voltage profile along the feeder for Case of failure of the proposed voltage regulation method.

4.4 Summary

A voltage regulation method is proposed by facilitating reactive power exchange by the PV inverters. It also defines proper reference voltages for the three phases of the network at each bus which will be used by the PV inverters. The method relies on the availability of smart meters at the buses along the LV feeder to transmit phase voltage measurements to the controllers of the PV inverters. The most effective voltage profiles which successfully captured demonstrate as the method was applied within the 24-hr periods. As the network have random load profiles, sun radiation and location/rating of the PVs over the certain period where the PV has successfully captured the best sun radiation over the 24-hr periods. The proposed voltage regulation by reactive power support methods is successful and recommended for LV networks with high penetrations of single-phase rooftop PVs.

CHAPTER 5

VOLTAGE UNBALANCED REDUCTION OF LV FEEDER BY ACTIVE POWER CURTAILMENT OF ROOFTOP PVs INVERTERS

5.1 Recent Studies

One of the main reasons for limiting the capacity with high penetration PV in the LV network is overvoltage. However, it is commonly avoided by limiting PV capacity along the feeder to very allowable values, even if the critical periods rarely occur. Droop based active power curtailment technique is able to overcome the overvoltage problem. Several recent studies have been conducted to demonstrate this technique into the LV network problem whenever PV is in the network.

In [40], it has been discussed that the active power curtailment technique can be implemented into two schemes. Firstly, all PV inverters that installed along the LV feeder have the same droop coefficients. In the second, the droop coefficients are different as it due to share the total active power curtailed among all PV inverters/houses. It describes the effectiveness of the proposed schemes and that the option of sharing the power curtailment among all customers derives at the cost of an overall higher amount of active power that has been curtailed. Other study [63] demonstrates that the active power curtailment technique has been successfully implemented in such a way which automatically adjusts their grid parameters by using a grid-impedance estimation method based on analysing the voltage and current variations at the point of common coupling (PCC) resulting from small deviations in the power generated by the voltage-source inverters (VSI).

Those studies have only considered three-phase PV systems. However, the situation is very divergent as different ratings single-phase PVs are installed unequally at different phases and buses throughout the LV network. Reference [41] investigates the active power curtailment approach for sizing and controlling the PV power generated by 12 net-zero energy houses equipped with large rooftop PV systems in a real system of 240V/75kVA Canadian sub-urban radial distribution feeder. The aim is to prevent overvoltage occurrence, sharing of the burden for overvoltage prevention per house and total energy yield of the residential PV feeder. Another implementation of gradual active power curtailment in order to minimize overvoltage problems which has been implemented into the real time system of the city urban feeder in Belgian Flanders region can be found in [64].

The voltage rise becomes a raising issue that discusses in [65]. It is due to active power injection and small *X/R* ratios in LV feeders restrict the amount of power to be installed in a hosting network. As a result, customers located at the end of the line will suffer from undesired overvoltage. For the duration of high PV generation and low load periods occur, a possibility of reverse power flow appears, and as a result, voltage rise problems arise in the LV feeder [65-72]. The droop based curtailment from PV generation [41] and [73]. Frequency droop, voltage droop with linkage to real or reactive power, all possible combinations are explored. Considering LV line characteristics voltage droop linkage with real power (P/V droop or the reverse droop) is the most effective combination.

However, curtailing active power generation from PV inverters to prevent voltage rise is proposed is not favourable strategy due to the possible loss of green energy that could have been harnessed using alternative approaches [74]. It has been support by another study, which present the disadvantage of active power curtailment method which is cause the spilling of solar energy, which is not economically attractive to the PV panel owners. [75].

This chapter will evaluate and analyse the proposed voltage unbalanced reduction by active power curtailment technique. Several considered cases that have been simulated through the two previous methods (voltage adjustment using OLTC transformer and voltage regulation by reactive power support) will be implemented using the active power curtailment method.

5.2 Simulation Results of Developed Case Studies

Due to highlight the voltage rise issue that caused by the high penetration of PV in the three-phase residential LV feeder, five case studies have been considered. The five considered case studies have the equivalent system configuration as they applied using the method of voltage adjustment using OLTC transformer and voltage regulation by reactive power support, which have been discussed in Chapter 3 and 4 respectively. Figure 5.1, 5.2, 5.3, 5.4 and 5.5 illustrate the voltage profile before and after improvement for all considered cases by applying voltage unbalanced reduction by active power curtailment method.

Table 5.1 Voltage magnitude for Case-1

	Voltage Profile (pu) before P Curtailment									
Bus / **Phase**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
A	1.0029	1.0056	1.007	1.0073	1.0079	1.0076	1.0071	1.0076	1.0075	1.0074
B	1.0021	1.0055	1.0075	1.0083	1.0069	1.004	1.0013	1.0006	1.0005	1.0005
C	1.0014	1.0031	1.0035	1.003	1.0016	0.9991	0.9972	0.9948	0.9941	0.9938
	Voltage Profile (pu) after P Curtailment									
Bus / **Phase**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
A	1.0012	1.0027	1.0032	1.0028	1.0032	1.0029	1.0024	1.0028	1.0027	1.0027
B	1.0007	1.003	1.0042	1.0044	1.0028	0.9999	0.9972	0.9965	0.9964	0.9964
C	0.9998	1.0004	1	0.999	0.9973	0.9948	0.9929	0.9905	0.9898	0.9895

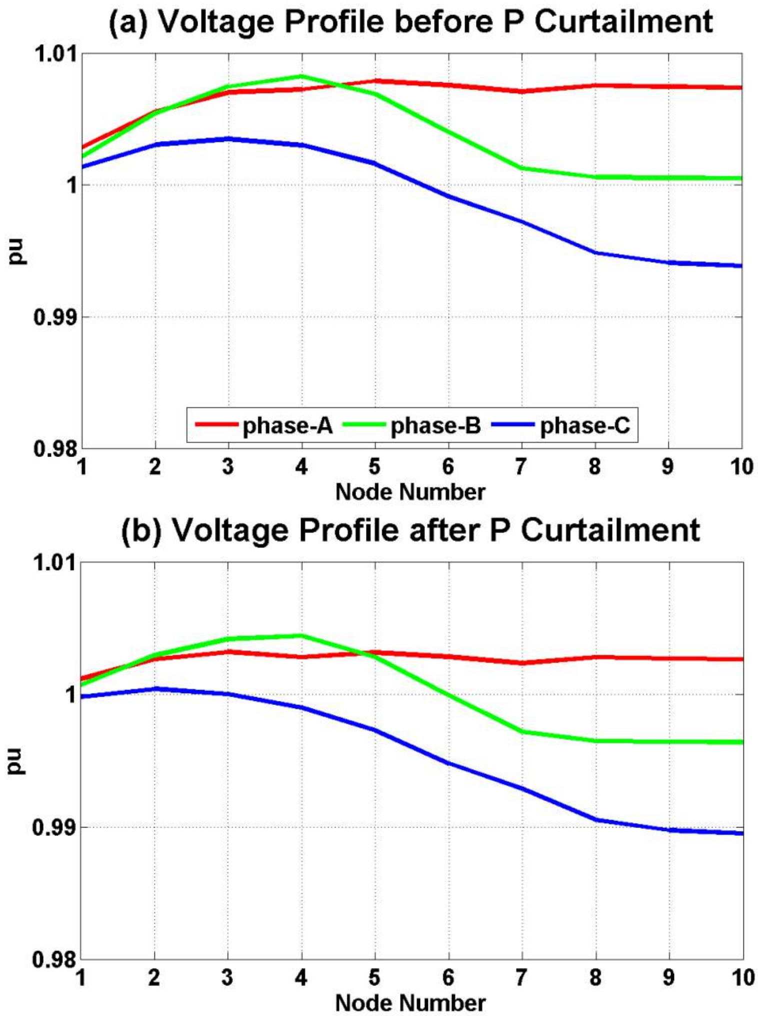

Figure 5.1. Three-phase voltage profile along the feeder for Case-1.

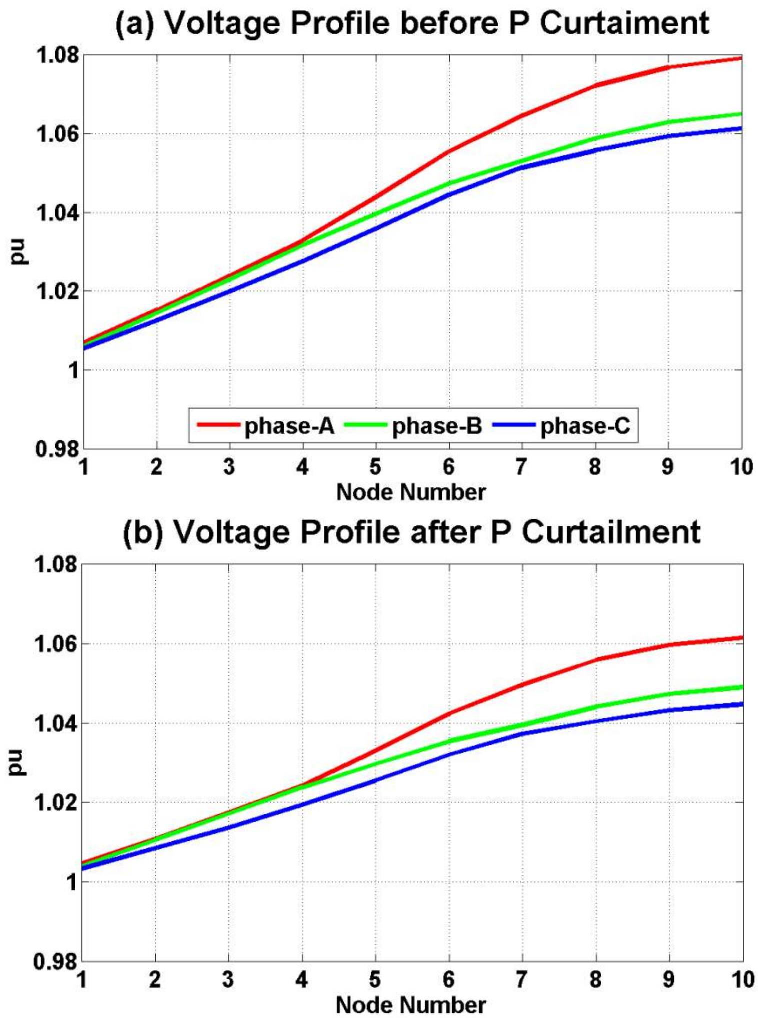

Figure 5.2. Three-phase voltage profile along the feeder for Case-2.

Each of these figures illustrates the voltage profiles before and after any improvements applying the proposed method. Through Figure 5.1b, it can be seen that active power curtailment method is not effective for voltage unbalanced reduction when majority of the PVs are in-stalled at the beginning buses of the feeder. Table 5.1 indicates the voltage magnitude in p.u. at every bus for phase-A, B and C as before and after curtailing the active power by PV inverters. As the rest tables (Table 5.2, 5.3, 5.4 and 5.5) indicate the same parameter which are illustrate in Figure 5.2, 5.3, 5.4, and 5.5, respectively.

As majority of the PVs are installed at the middle and end buses of the feeder, even though the unbalanced voltage profiles are reduced, but at the end of feeder of phase-A, it reaches the value beyond the acceptable limits (Figure 5.2b).

Table 5.2 Voltage magnitude for Case-2

	Voltage Profile (pu) before P Curtailment									
Bus	1	2	3	4	5	6	7	8	9	10
Phase										
A	1.0068	1.0152	1.0239	1.0329	1.0439	1.0555	1.0645	1.0721	1.0767	1.0791
B	1.006	1.0145	1.023	1.0317	1.0396	1.0473	1.0531	1.0587	1.0629	1.065
C	1.0055	1.0126	1.0199	1.0276	1.0359	1.0444	1.0514	1.0557	1.0593	1.0613
	Voltage Profile (pu) after P Curtailment									
Bus	1	2	3	4	5	6	7	8	9	10
Phase										
A	1.0047	1.0109	1.0174	1.0242	1.033	1.0424	1.0496	1.0559	1.0596	1.0615
B	1.004	1.0105	1.0171	1.0238	1.0297	1.0354	1.0396	1.044	1.0473	1.049
C	1.0034	1.0085	1.0137	1.0194	1.0256	1.0321	1.0373	1.0404	1.0432	1.0447

As for Case-3, where All houses connected to phase-A have rooftop single-phase rooftop PVs while only a small portion of the houses connected to phase-B and C have PVs, Figure 5.3b represents a very significant improvement of the active power curtailment method to reduce voltage unbalanced in the LV network. As can be seen, the voltage profiles set within the allowable limits. When the voltage unbalanced reduction of LV feeder by active curtailment of PV inverters method is applied to Case-4, where all houses connected to phase-B have rooftop single-phase rooftop PVs while only a small portion of the houses connected to phase-A and C have PVs. Less reduction of voltage unbalanced occurs, as illustrates in Figure 5.4b.

Table 5.3 Voltage magnitude for Case-3

	Voltage Profile (pu) before P Curtailment									
Bus / Phase	1	2	3	4	5	6	7	8	9	10
A	1.0124	1.0251	1.0369	1.046	1.0559	1.0655	1.0728	1.0788	1.0824	1.0837
B	0.9922	0.9882	0.9849	0.9821	0.9792	0.9767	0.9725	0.9717	0.9725	0.9718
C	1.0089	1.0188	1.0263	1.0341	1.042	1.0485	1.0531	1.0565	1.0587	1.0623
	Voltage Profile (pu) after P Curtailment									
Bus / Phase	1	2	3	4	5	6	7	8	9	10
A	0.9997	1.0005	1.0014	1.0016	1.0034	1.0056	1.0071	1.0089	1.0098	1.0099
B	0.9944	0.9922	0.9902	0.9884	0.986	0.9835	0.9804	0.9799	0.9802	0.9802
C	1.0007	1.0033	1.0049	1.0068	1.0092	1.011	1.0121	1.0125	1.0133	1.0148

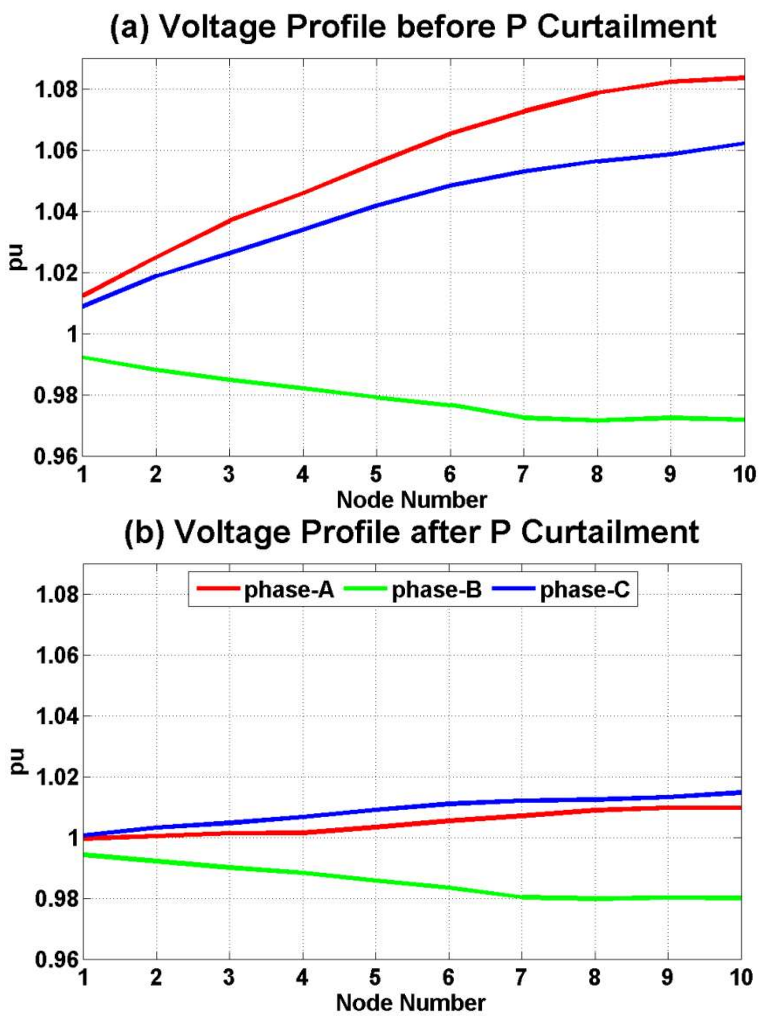

Figure 5.3. Three-phase voltage profile along the feeder for Case-3.

Table 5.4 Voltage magnitude for Case-4

	Voltage Profile (pu) before P Curtailment									
Bus / Phase	1	2	3	4	5	6	7	8	9	10
A	0.9967	0.9964	0.9958	0.9942	0.9958	0.9973	0.9975	0.9998	1.0009	1.0008
B	1.0008	1.0037	1.0048	1.0066	1.0069	1.0052	1.0043	1.0047	1.0039	1.0039
C	0.9998	0.999	0.9994	0.9998	0.9982	0.9979	0.9979	0.9948	0.9944	0.9942
	Voltage Profile (pu) after P Curtailment									
Bus / Phase	1	2	3	4	5	6	7	8	9	10
A	0.9962	0.9953	0.9941	0.9923	0.9934	0.9946	0.9946	0.9965	0.9974	0.9973
B	0.9996	1.0015	1.002	1.0031	1.0028	1.0009	0.9996	0.9998	0.9992	0.9991
C	0.9986	0.9972	0.9967	0.9965	0.9946	0.9938	0.9934	0.9905	0.99	0.9898

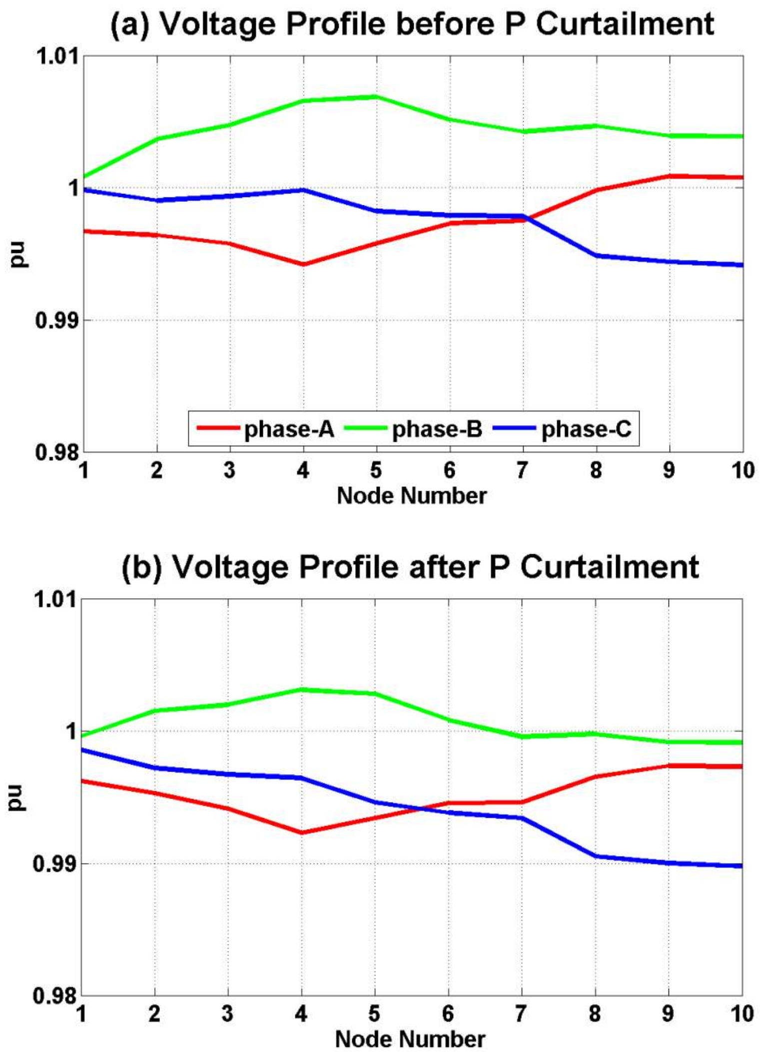

Figure 5.4. Three-phase voltage profile along the feeder for Case-4.

Furthermore, when the proposed method applied to Case-5, the network voltage profiles are evaluated over a 24-hr period. The results clearly indicate that due to the number and ratings of the PVs, the proposed method is effective in reducing voltage unbalanced, but it occurs that the voltage profiles set beyond the allowable limit (Figure 5.5b).

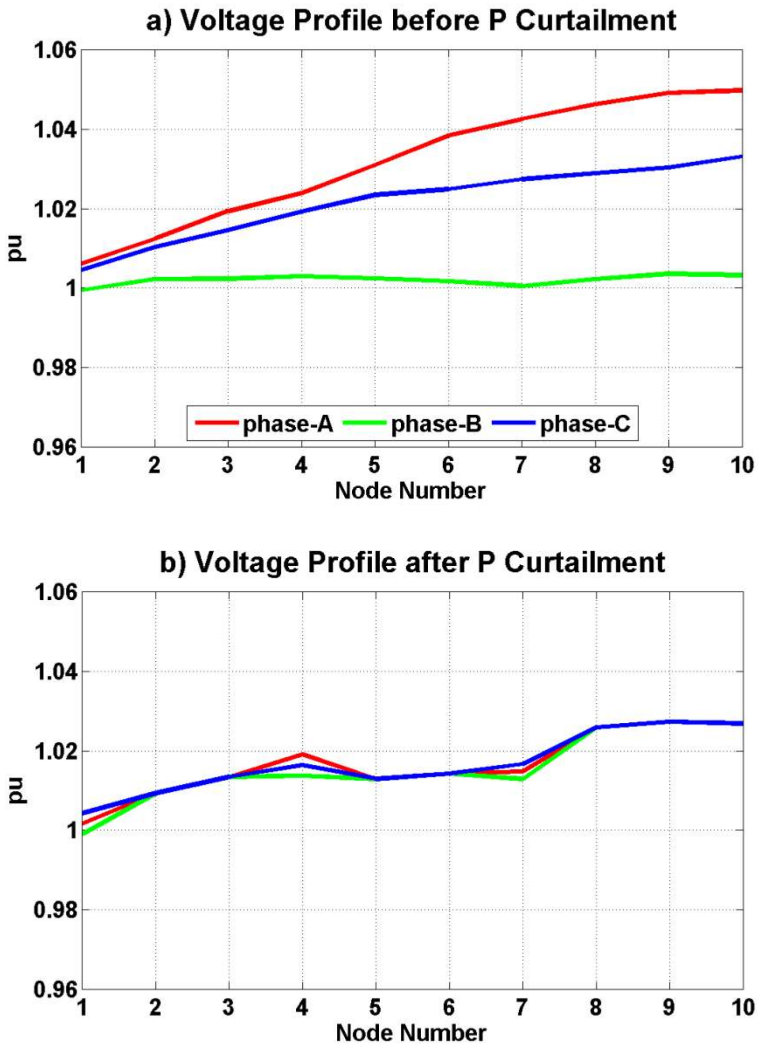

Figure 5.5. Three-phase voltage profile along the feeder for Case-5.

Table 5.5 Voltage magnitude for Case-5

	Voltage Profile (pu) before P Curtailment									
Bus / Phase	1	2	3	4	5	6	7	8	9	10
A	1.0063	1.0129	1.0202	1.025	1.0321	1.0398	1.0447	1.0484	1.0518	1.0527
B	1.0009	1.0036	1.0036	1.005	1.0057	1.0074	1.008	1.0101	1.0111	1.0107
C	1.0024	1.0073	1.0111	1.0152	1.0198	1.0207	1.0226	1.0245	1.0265	1.0299
	Voltage Profile (pu) after P Curtailment									
Bus / Phase	1	2	3	4	5	6	7	8	9	10
A	1.0022	1.0093	1.0132	1.0191	1.0133	1.015	1.016	1.0239	1.0251	1.0248
B	1.0004	1.0093	1.0132	1.0134	1.0133	1.015	1.0147	1.0239	1.0251	1.0248
C	1.004	1.0093	1.0132	1.0162	1.0133	1.015	1.0174	1.0239	1.0251	1.0248

5.3 Limitation of the Voltage Unbalanced Reduction by Active Power Curtailment Method

In certain considered cases, the voltage profiles cannot be improved as effectively as expected. It approves that the proposed method only successfully applied when high penetration of PVs occur in the LV feeder. As the schemes of the considered cases have various ratings of single-phase PVs (1-5kW), and randomly distributing their generating power along the feeder. In addition, the dependency of the proposed method on the communication technology can cause limitations for the proposed method if the data transfer is interrupted at any unpredictable situations.

Another case was developed to mitigate the failure of the proposed unbalanced voltage reduction method. In this considered case, the network of Figure 2.1 in which ten single-phase PVs are installed at all buses of only one phase (in this case phase-B). Table 5.6 describes the PV inverter rating and location along the feeder for phase-A, B and C.

Table 5.6. PV inverter ratings (in kVA) for single-phase rooftop PVs, considered in the simulation of failure of the proposed unbalanced voltage reduction method.

Bus No.	1	2	3	4	5	6	7	8	9	10
Phase	Case of failure of the proposed unbalanced voltage reduction method									
A	0	0	1	0	0	1	0	0	1	0
B	1	1	1	1	1	1	1	1	1	1
C	0	0	1	0	0	1	0	0	1	0

Figure 5.6 illustrates the failure of applying the unbalanced voltage reduction by active power curtailment of PVs inverters in the LV feeder. Table 5.6, indicates that the number and ratings of PVs in each phase is uniformly 1kW.

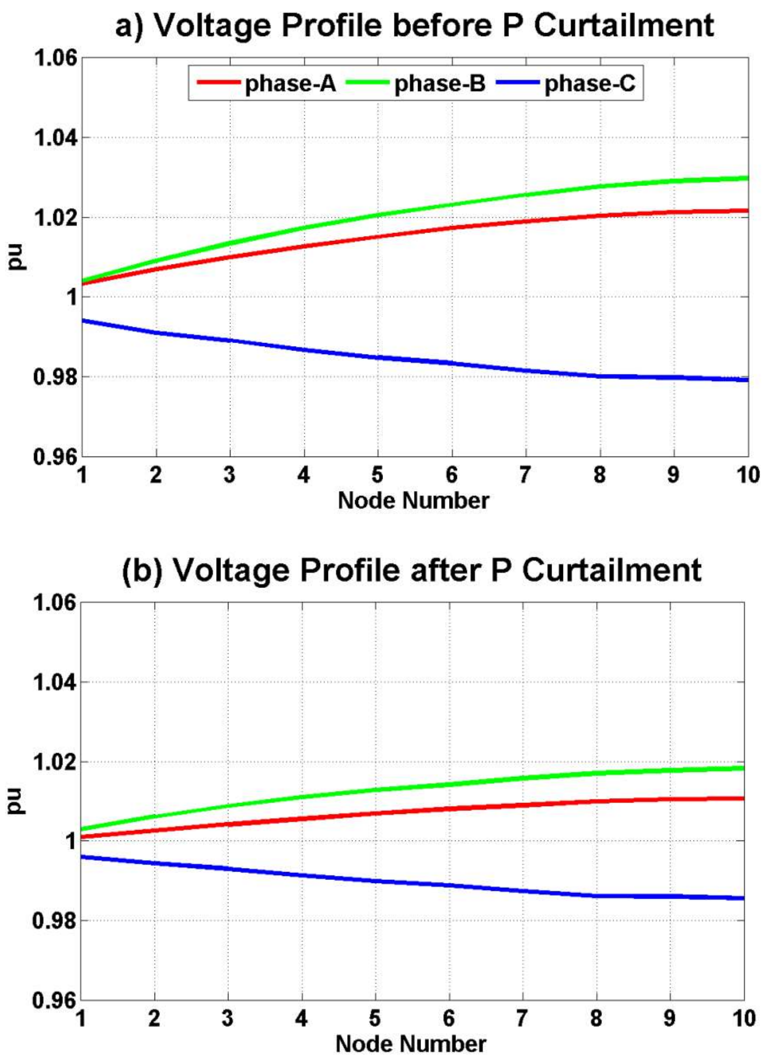

Figure 5.6. Three-phase voltage profile along the feeder for Case of failure of the proposed unbalanced voltage reduction method.

As can be seen from Figure 5.6a, before applying the proposed method, the voltage profiles are within the acceptable limits. After applying the proposed method (Figure 5.6b), it appears that the method is unsuccessful to reduce voltage unbalanced though the voltage profiles are still in the acceptable limits. It is because the number and rating of PVs along the feeder are very small. The voltage magnitude in p.u. for every bus along the feeder, before and after curtailing active power by PV inverters can be seen in Table 5.7.

Table 5.7 Voltage magnitude for failure case

	Voltage Profile (pu) before P Curtailment									
Bus	1	2	3	4	5	6	7	8	9	10
Phase										
A	1.0027	1.0058	1.0087	1.0112	1.0135	1.0155	1.0171	1.0185	1.0194	1.0197
B	1.0055	1.0107	1.0152	1.0191	1.0223	1.0248	1.0274	1.0293	1.0304	1.0312
C	0.9956	0.9934	0.9918	0.9896	0.9879	0.9867	0.9849	0.9836	0.9835	0.9829
	Voltage Profile (pu) after P Curtailment									
Bus	1	2	3	4	5	6	7	8	9	10
Phase										
A	1.001	1.0026	1.0042	1.0056	1.0069	1.0081	1.009	1.01	1.0105	1.0107
B	1.003	1.0061	1.0088	1.011	1.0128	1.0142	1.0158	1.017	1.0178	1.0183
C	0.9961	0.9944	0.993	0.9913	0.9899	0.9889	0.9874	0.9862	0.9861	0.9856

5.4 Summary

MATLAB-based simulation results which demonstrated as various schemes in the considered cases show the effectiveness of the proposed method for the network with random load profiles, sun radiation and location/rating of the PVs over 24-hr periods. The proposed method will be successful and recommended for LV networks with high penetrations of single-phase rooftop PVs. Additionally, the effectiveness of the proposed method can be evaluated for different uncertain and random conditions of load profile and sun radiation with different ratings/locations of PVs using stochastic analysis.

CHAPTER 6

COORDINATION OF SINGLE-PHASE ROOFTOP PVs IN UNBALANCED THREE-PHASE RESIDENTIAL FEEDERS FOR VOLTAGE PROFILE IMPROVEMENT

6.1 Evaluation of Proposed Methods

In advance, the proposed methods which are consisting three different techniques that are separately discussed in Chapter 3, 4 and 5 are recapped in Table 6.1.

Table 6.1. Summary of the effectiveness of each step in voltage rise and voltage unbalance control for the simulation study cases 1, 2 and 3.

Voltage Control Techniques	Voltage Rise Control			Voltage Unbalance Control		
	Case-1	Case-2	Case-3	Case-1	Case-2	Case-3
Step-1	✓	✓	✓	×	×	×
Step-2	✓	×	✓	✓	✓	✓
Step-3	✓	✓	✓	×	×	×
Proposed Technique (Consisting of All Three Steps)	✓	✓	✓	✓	✓	✓

To perform the simulation studies, instead of the actual data measured from the smart meters, an unbalanced load flow analysis is carried out to define the voltages throughout the LV feeder; however, in a real system with smart meters and communication infrastructure, there is no need for the load flow analysis. This chapter discuss the proposed methods put together in one step as voltage regulation techniques in order to enhance voltage profile improvement in the unbalanced three-phase residential feeder with coordination of single-phase rooftop PVs. The case to be considered in this chapter is the network voltage profiles are evaluated over a 24-hr period.

Since the LV network load and PV output power generation are time variant, then they vary within 24-hr period for winter/summer seasons. For that reason, it is possible that a certain network could have hundreds of different load demands and PV output power generation patterns. Moreover, the number of installed single-phase rooftop PVs by householders within the LV network will increase, with the random ratings and location. Thus, an evaluation is essential to mitigate all the random data for a certain network [76]. Table 6.1 describes the included parameters of the stochastic evaluation for the considered 24-hr period case study.

As an additional stage, the discussed methods can be considered within an optimization problem to achieve better results in voltage regulation with minimum effort on OLTC operation, reactive power support and active power curtailment. Essentially, the effectiveness of the proposed method can be assessed for different uncertain and random conditions of load profile and sun radiation with different ratings/locations of PVs using stochastic evaluation. To evaluate the performance of the proposed method for a network under different load and PV profiles, another case study is considered. In this study, the network voltage profiles are evaluated over a 24-hr period. The data of an urban residential LV network in Perth, Australia is utilized for this study. The residential load profiles used in this analysis are based on the real data captured from smart meters installed in the network in 15-min intervals [77-78].

Moreover, a PV penetration level of 60% is considered which is twice of the accepted PV penetration level by Australian utilities [65] to evaluate the effectiveness of the proposed method. In addition, the considered PVs have a normal distribution with an average of 3.5 kW and a standard deviation of 1.1 kW. The number of PVs installed in each phase is also selected based on a normal distribution with an average of 33% per phase and a standard deviation of 30%. In addition, the sunlight availability is assumed between 6.00 am and 6.00 pm while the PVs generate their maximum output at 12.00 noon, considering the sun radiation in Perth, Australia [57] in summer. To consider the clouds effect on the PV output power generation, a white noise signal is added to the output power of the PVs. Since the PVs are located in a close geographic area (400 m) the same PV output power characteristic is used for all considered PVs in the network.

6.2 Simulation Results of the Coordination of the Proposed Methods

Coordinated voltage control methods define their control actions according to the essential information and data transfer between network nodes. In advanced, coordinated voltage controls in distribution systems have been developed with different levels of complexity, effectiveness, and essential communications. For examples, coordination of distribution network components such as switched capacitor control and OLTC of transformer. Also take into account an innovative controller that coordinates the OLTC feature of the transformer with the regulation of reactive power exchanges and the active power curtailment amongst the generated single-phase rooftop PVs along the LV feeder.

The OLTC feature of the distribution transformer of the LV feeder can adjust the voltage level by lowering the tap position of the OLTC distribution transformer if voltage rise beyond the allowable limits is detected at the end of the feeder. From this point, the voltage profiles of the unbalanced three-phase LV feeder also can be regulated by facilitating reactive power exchange of the PV inverters. Also the active power curtailment of PV inverter can be utilized to reducing the unbalance voltage of the LV feeder whenever the high PV penetration occurs.

The coordination of the proposed approaches also defines proper reference voltages for the three phases of the network at each bus which will be used by the PV inverters. Nevertheless, this method eventually relies on the availability of smart meters at the buses along the LV feeder to transmit phase voltage measurements to the controllers of the PV inverters.

Figure 6.1 and 6.2 illustrate the 24-hr period of PV generating power. The dashed and solid lines represent the voltage profiles before and after the unbalanced three-phase residential LV feeder with single-phase rooftop PVs applying all the proposed methods together, respectively. Figure 6.1 illustrates the voltage profiles at 01.00 am to 12.00 noon time during the 24-hr period. Then Figure 6.2 demonstrates the voltage profiles at 01.00 pm to 12.00 night time. The results demonstrate the effectiveness of the proposed method in voltage profile regulation and unbalance reduction. However, four best samples that shown the methods are successfully implemented are at 9.00 am (Figure 6.1), 2.00 pm, 3.00 pm and 4.00 pm (Figure 6.2). It is to be noted that, there is no difference in the voltage profiles in the duration of midnight to 6.00 am in the morning and 6.00 pm in the afternoon to midnight since the PVs are not generating any power.

The 24-hr load profiles of the network are illustrated for all the 10 buses of the network in Figure 6.3 and 6.4. The voltage profiles are shown before and after applying the proposed voltage regulation method. Through these results, it can be seen that even for a 60% penetration level of PVs (i.e. twice of the current allowable limit for PV installation in the network by Australian utilities), the proposed methods applying together successfully prevent high voltage rise at feeder end nodes (Bus-10) and effectively reduces the voltage unbalance. The voltage magnitudes have been captured every 15 minutes. Every bus will have 96 different values of voltage magnitudes. Voltage magnitudes in p.u. of every bus are presented in appendix B.

MATLAB-based simulation results demonstrate effectiveness of the proposed method for the network with random load profiles, sun radiation and location/rating of the PVs over 24-hr periods. The proposed methods will be successful and recommended for LV networks with high penetrations of single-phase rooftop PVs. The summary of the effectiveness of the proposed voltage regulating technique on voltage rise and unbalance control over 24-hr period is given in Table 6.2 for the considered system.

Table 6.2. Summary of the effectiveness of the proposed voltage regulating technique on voltage rise and unbalance control over 24-hr period.

	Beginning nodes	Middle nodes	End nodes
Within PV generation Period	✓	✓	✓
Outside PV generation Period	No difference	No difference	No difference

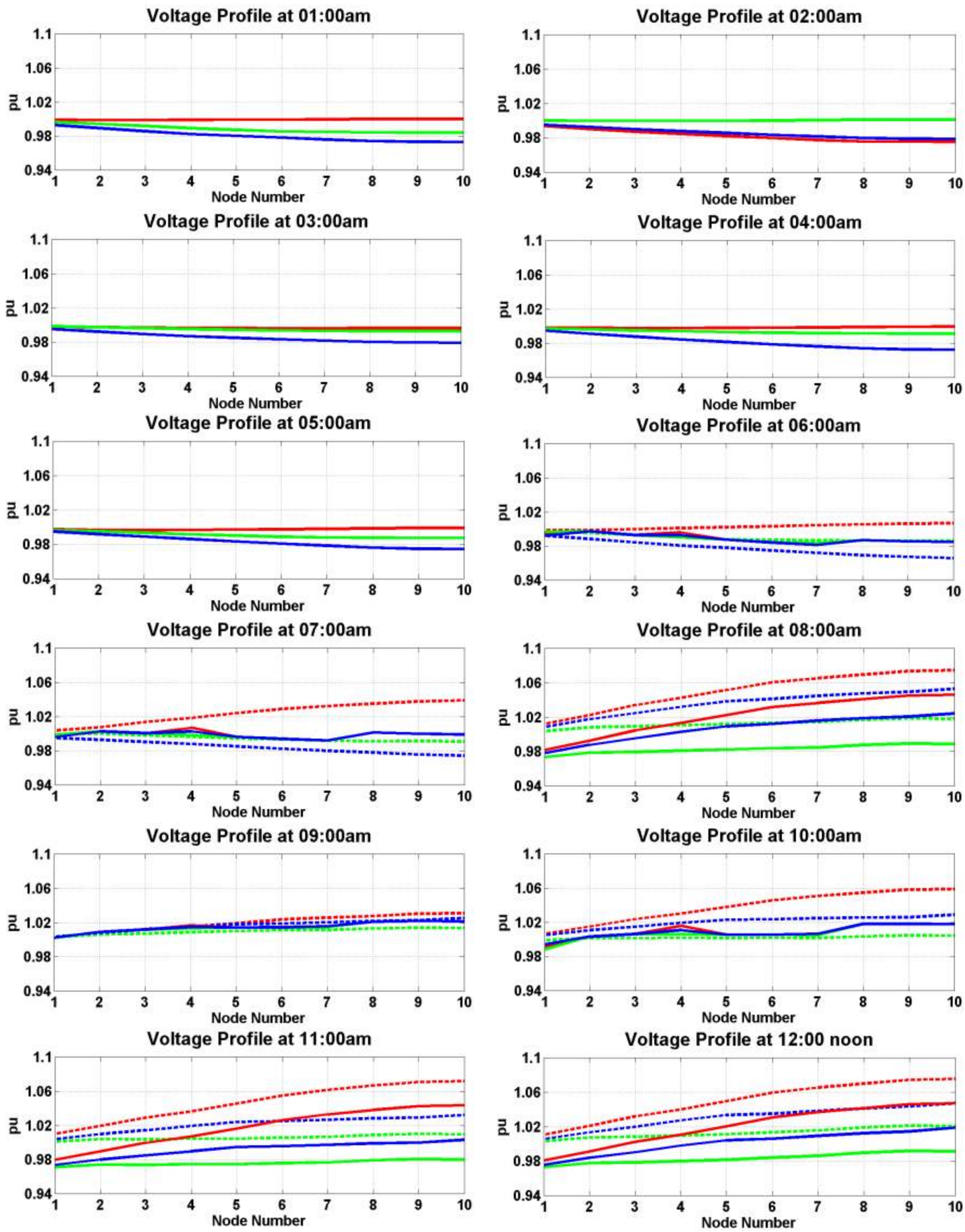

Figure 6.1. Voltage profile of the considered case study before and after improvement at 01.00 am to 12.00 noon during the 24-hr period.

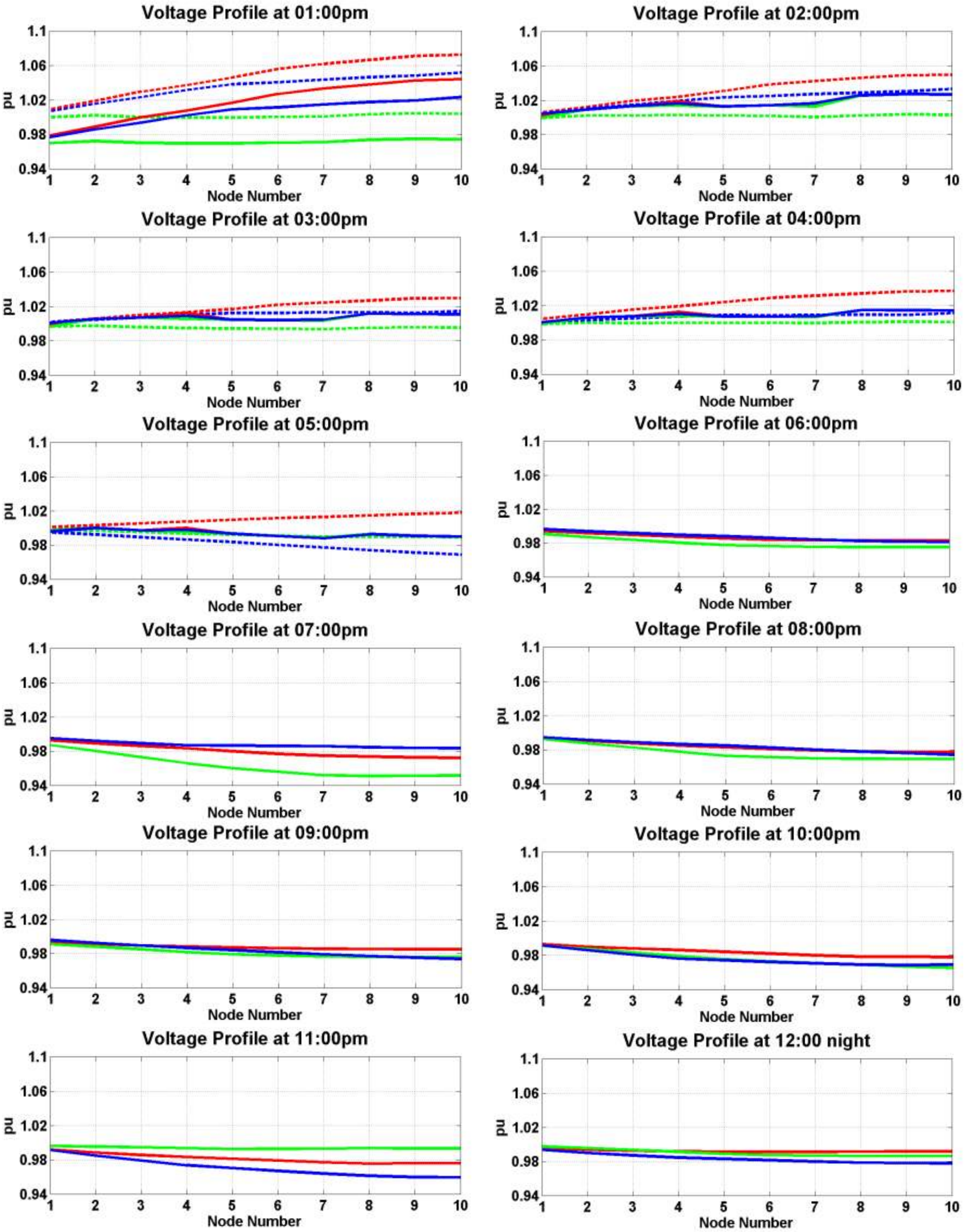

Figure 6.2. Voltage profile of the considered case study before and after improvement at 01.00 pm to 12.00 night during the 24-hr period.

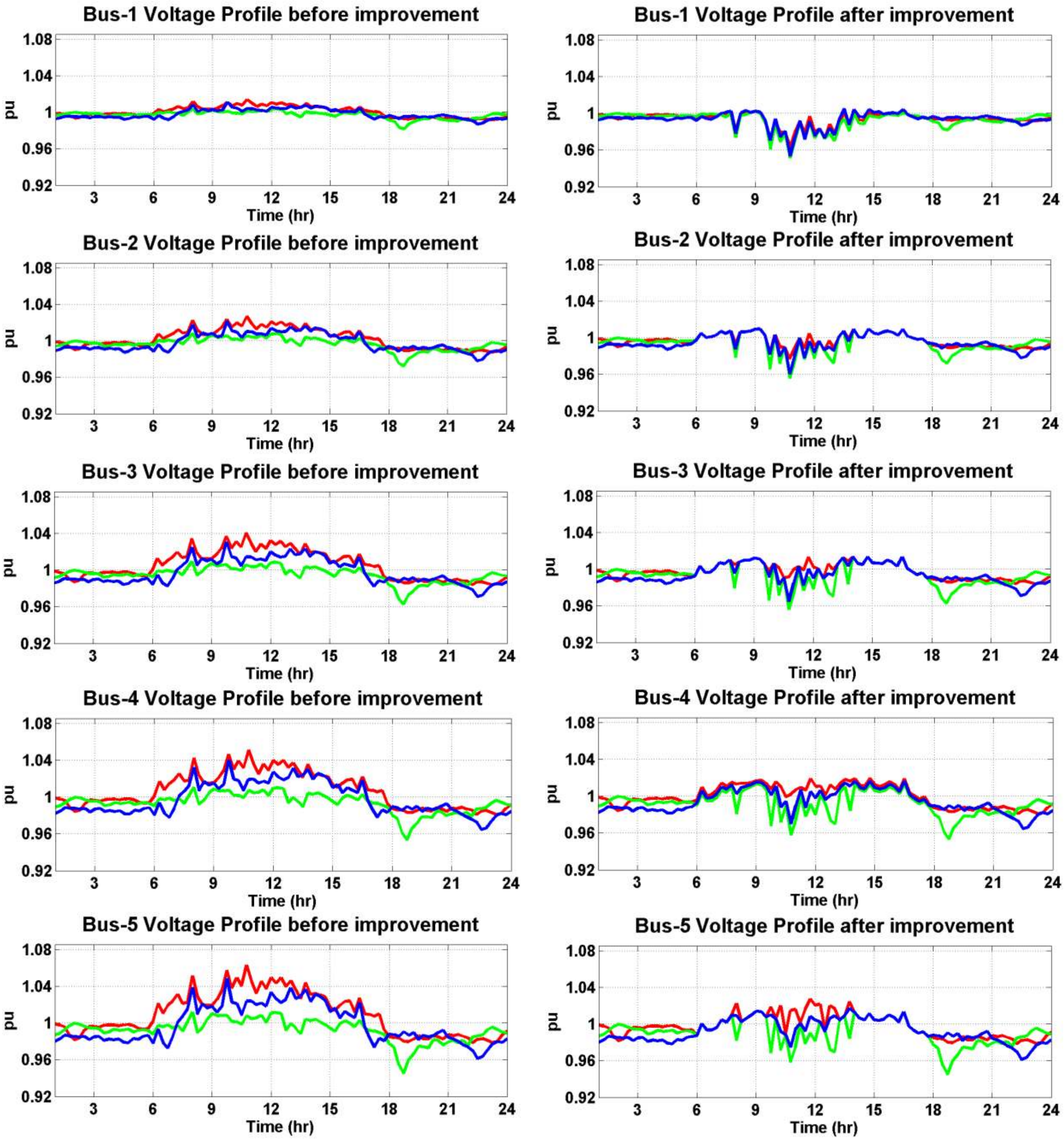

Figure 6.3. Voltage profile at Bus-1 to 5 before and after improvement.

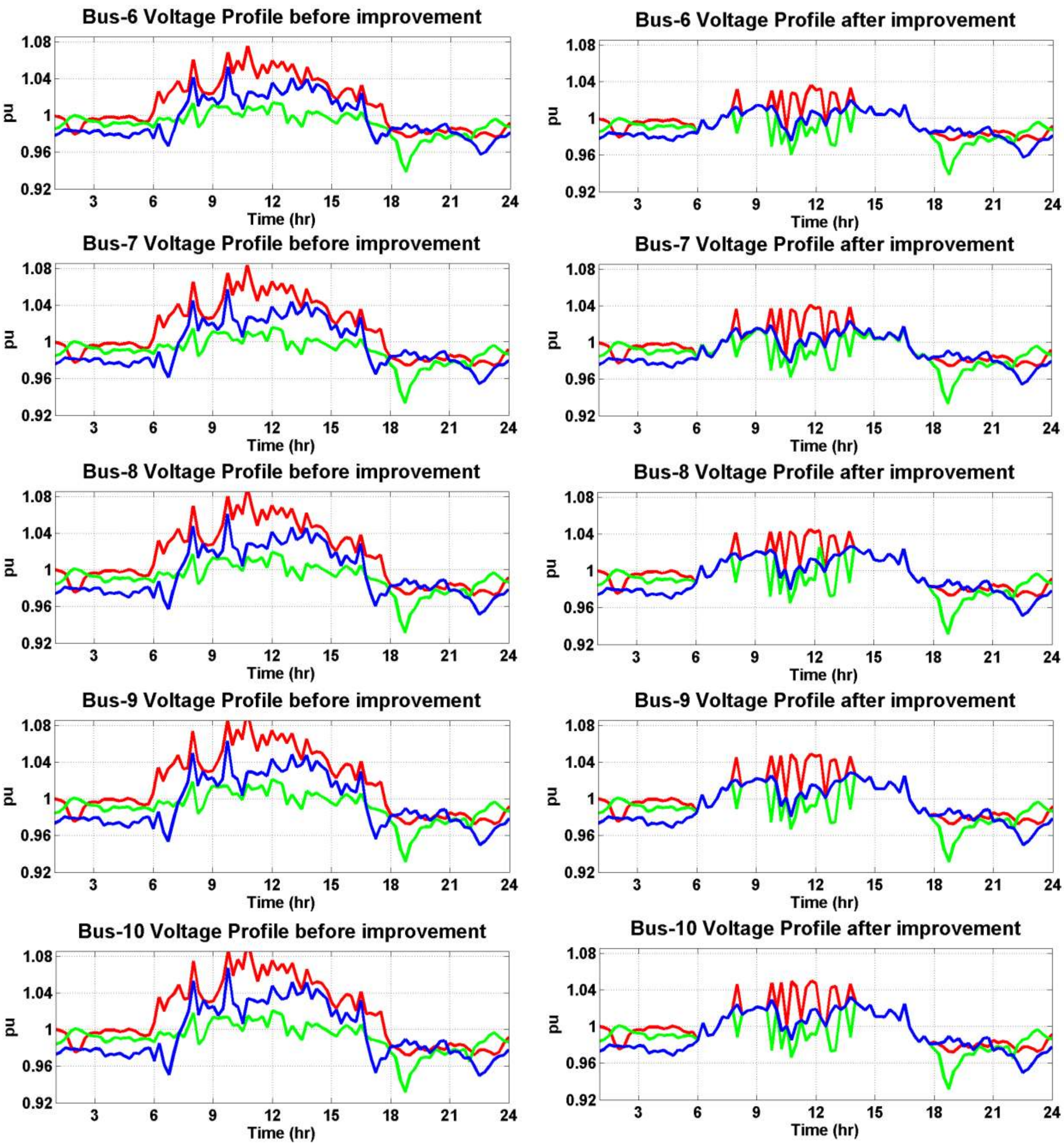

Figure 6.4. Voltage profile at Bus-6 to 10 before and after improvement.

6.3 Limitation of the Coordination of the Proposed Methods

Each of the proposed methods has several benefits and drawbacks. They have been shown clearly through the simulation results and have been developed based on schemes of considered case studies. The main limitation of the proposed method is when all or majority of the PVs are installed only at one phase. In addition, the second limitation of the method is when the PV inverters do not have a minimum of 10-20% higher rating compared to rated active power generated by the solar cells. Other limitation is the proposed coordination method is very much depends on data communication system and also the number and ratings of PVs in each phase, particularly at low penetrations of rooftop PVs.

CHAPTER 7

CONCLUSION AND RECOMMENDATION

7.1 Conclusion

The number of single-phase rooftop PVs in low voltage distribution networks are increasing and the utilities have recently adopted limitations on the maximum number of rooftop PVs that can be installed by householders of a feeder to prevent probable voltage rise and unbalance problems. A voltage regulation method is proposed in this thesis, which is composed of three steps of adjusting the voltage level by OLTC transformer and reducing the voltage unbalance by facilitating reactive power exchange and active power curtailment by the PV inverters. The approach consists of lowering the tap position of the OLTC distribution transformer if non-standard voltage rise is detected at the end of the feeder. It also defines proper reference voltages for the three phases of the network at each bus which will be used by the PV inverters. The method relies on the availability of smart meters at the buses along the LV feeder to transmit phase voltage measurements to the controllers of the PV inverters.

MATLAB-based simulation results demonstrate effectiveness of the proposed method for the network with random load profiles, sun radiation and location/rating of the PVs over 24-hr periods. The proposed methods will be successful and recommended for LV networks with high penetrations of single-phase rooftop PVs. The main limitation of the proposed method is its dependency on data communication system and also the number and ratings of PVs in each phase, particularly at low penetrations of rooftop PVs.

As a further step, the methods that have been discussed earlier can be considered within an optimization problem to achieve better results in voltage regulation with minimum effort on OLTC operation and active power curtailment. Additionally, the effectiveness of the proposed method can be evaluated for different uncertain and random conditions of load profile and sun radiation with different ratings/locations of PVs using stochastic analyses.

7.2 Recommendation for Future Research

There are three scopes for further continue the research in the future. These researches including mitigate the OLTC dynamic characteristic and control mechanism and its transient effect, take into account the communication systems including the interruptions/delays, and observe the possibility of using battery storage unit for the single-phase rooftop PV system.

7.2.1 Studying Dynamic Characteristic and Control Mechanism of OLTC

In order to enhance the transient stability of single-phase rooftop PVs using OLTC equipped transformer, a dynamic study to determine the characteristic and control mechanism of OLTC must take into account. It is well known that the PVs reverse power flow can increase the number of OLTC tap operations under certain system conditions at the high level of PVs penetrations. In this study, several simulations of the occurred transient will be investigated due to maintain the voltage profiles within the permissible limits. This recommended study can be considered within an optimization problem to regulate voltage profile in LV residential feeder with minimum effort on OLTC operation.

7.2.2 Studying Communication System, Interruptions and Delays

An intelligent and communication-based voltage profile regulating technique is proposed in this thesis which is composed of three steps of adjusting the voltage level by OLTC transformer and reducing the voltage unbalance by facilitating reactive power exchange and active power curtailment by the PV inverters, simultaneously. The interoperability of PV inverters and utilities devices within the LV residential network in one way or another now are microprocessor-based controllers. In addition, the interruptions such as different manufactures which are not able to interoperate due to compatibility issues and missing communication standard might frequently occur. Delays might also occur during the operating time. For this reasons, it is very highly recommended to overcome the interruptions and delays within an optimization problem to achieve better results in voltage regulation with minimum effort on OLTC operation and active power curtailment.

7.2.3 Studying Battery Storage Units

Voltage improvement and regulation through droop-based control of adjusting the voltage level by OLTC transformer and reducing the voltage unbalance by facilitating reactive power exchange and active power curtailment by the PV inverters will only be effective up to a certain level of loading. Furthermore, it is only possible to perform voltage regulations during the day while most of the large smart appliances such as PEVs are usually activated in the evening and/or early morning hours when the price of the electricity are expected to be inexpensive. Therefore, distributed battery storage units are assumed to be available at the household with the single-phase rooftop PVs.

The battery can be assumed as a constant voltage source with fixed amount of energy and modelled as a constant DC voltage source with series internal resistance. Since the battery has a limitation on the duration of its generated power depending on the amount of current, then it will be assumed that the battery will be charged at off-peak load periods. This could be another interesting topic to be deployed.

REFERENCES

[1] Student Report, Group PED4 - 1043. “Control of Grid Connected PV Systems with Grid Support Function”. Department of Energy Technology Pontoppidanstaede 101 Aalborg University, Denmark; 2012.

[2] F. Shahnia, A. Ghosh, G. Ledwich and F. Zare, "Voltage unbalance reduction in low voltage distribution networks with rooftop PVs," in Universities Power Engineering Conference (AUPEC), 2010, pp . 1-5.

[3] N. Safitri, F. Shahnia, M.A.S Masoum, “Coordination of single-phase rooftop PVs to regulate voltage profiles of unbalanced residential feeders,” in 24th Australasian Universities Power Engineering Conference (AUPEC) 2014.

[4] F. Shahnia, “*Analysis and Correction of Voltage Profile in Low Voltage Distribution Networks Containing Photovoltaic Cells and Electric Vehicles*”, [Doctor of Philosophy]. Queensland: Queensland University of Technology; 2011.

[5] F. Shahnia, R. Majumder, A. Ghosh, G. Ledwich and F. Zare, " Sensitivity analysis of voltage imbalance in distribution networks with rooftop PVs," in Power and Energy Society General Meeting, 2010 IEEE, 2010, pp. 1-8.

[6] VDE-AR-N 4105, "Generators connected to the low-voltage distribution network - Technical requirements for the connection to and parallel operation with low-voltage distribution networks," 2011.

[7] A. Gosh, G. Ledwich, “*Power Quality Enhancement Using Custom Power Devices*”, Kluwer Academic Publisher; 2002.

[8] F. Shahnia, A. Ghosh, G. Ledwich and F. Zare, “Voltage correction in low voltage distribution networks with rooftop PVs using custom power devices,” in 37th Annual Conference on IEEE Industrial Electronics Society, p. 991-6, 2011.

[9] Australian Standard Voltage, AS60038–2000.

[10] IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) IEEE Std2000, p. 929-2000, 2000.

[11] S. Conti, A. Greco, N. Messina, S. Raiti, “Local voltage regulation in LV distribution networks with PV distributed generation Power Electronics, Electrical Drives,” Automation and Motion International Symposium, p. 519-24, 2006.

[12] N. Safitri, F. Shahnia, M.A.S Masoum, “Different techniques for simultaneously increasing the penetration level of rooftop PVs in residential LV networks and

improving voltage profile," 6th IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC 2014) 2014.

[13] P. Trichakis, *et al.*, "Predicting the technical impact of high level of small-scaled embedded generators on low-voltage networks," in Renewable Power Generation, IET, vol. 2, p. 249-262, 2008.

[14] P. Trichakis, *et al.*, "An investigation of voltage unbalance in low voltage Distribution networks with high levels of SSEG," in Universities Power Engineering Conference (UPEC), p. 182-6, 2006.

[15] Y. Ruifeng, T.K. Saha, "Voltage variation sensitivity analysis for unbalanced distribution networks due to photovoltaic power fluctuations," in IEEE Trans on Power Systems, 27:1078-89, 2012.

[16] R. Tonkoski, L.A.C. Lopes and T.H.M. El-Fouly, "Droop-Based Active Power Curtailment for Overvoltage Prevention in Grid Connected PV Inverters," IEEE Int Symp on Industrial Electronics (ISIE), p. 2388-2393, 2010.

[17] F. Shahnia, A. Ghosh, "Decentralized Voltage Support in a Low Voltage Feeder by Droop based Voltage Controlled PVs," in 23rd Australasian Universities Power Engineering Conference (AUPEC), p. 1-5, 2013.

[18] Y. Liu, J. Bebic, B. Kroposki, *et al.*, "Distribution System Voltage Performance Analysis for High-Penetration PV, " in IEEE Energy 2030 Conference, p. 1-8, 2008.

[19] D. Dohnal, "*On-Load Tap-Changers for Power Transformers*," Germany: Maschinenfabrik Reinhausen GmbH; 2013.

[20] IEEE recommended practice for monitoring electric power quality, IEEE Standard 1159–1995.

[21] A. Scognamiglio1 and H. N. Røstvik, "Photovoltaics and zero energy buildings: a new opportunity and challenge for design," in Prog. Photovolt: Res. Appl. 2013; 21:1319–1336, DOI: 10.1002/pip.2286, wileyonlinelibrary.com, 2012.

[22] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, "A Three-Phase Power Flow Approach for Integrated 3-Wire MV and 4-Wire Multigrounded LV Networks With Rooftop Solar PV," in IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 28, NO. 2, MAY 2013.

[23] L. Poh Chiang, L. Ding, and F. Blaabjerg, "Autonomous Control of Interlinking Converters in Hybrid AC-DC Microgrids with Energy Storages," in Energy Conversion Congress and Exposition (ECCE), 2011 IEEE, pp. 652-658, 2011.

[24] E. Demirok, D. Sera, R. Teodorescu, P. Rodriguez and U. Borup, “Clustered PV inverters in LV Networks: An overview of impacts and comparison of voltage control strategies,” in IEEE Electrical Power & Energy Conference, 2009.

[25] G. Ledwich and A. Ghosh, "Vector Droop Line Compensation Analysis," in Innovative Smart Grid Technologies Asia (ISGT), 2011 IEEE PES, 2011, pp. 1-6.

[26] K. Yao, K. Lee, M. Xu, and F. C. Lee, "Optimal Design of the Active Droop Control Method for the Transient Response," in Applied Power Electronics Conference and Exposition, 2003. APEC '03. Eighteenth Annual IEEE, 2003, pp. 718-723 vol.2.

[27] K. De Brabandere, B. Bolsens, J. Van den Keybus, A. Woyte, J. Driesen, and R. Belmans, "A Voltage and Frequency Droop Control Method for Parallel Inverters," Power Electronics, IEEE Transactions on, vol. 22, pp. 1107-1115, 2007.

[28] A. Engler and N. Soultanis, "Droop Control in LV-Grids," in Future Power Systems, 2005 International Conference on, 2005, pp. 6 pp.-6.

[29] I. C. Vasquez, R. A. Mastromauro, J. M. Guerrero and M. Liserre, “Voltage support provided by a droop-controlled multifunctional inverter,” in IEEE Trans on Industrial Electronics, p. 56:4510-4519, 2009.

[30] N. Efkarpidis, C. Gonzalez, T. Wijnhoven, D. V. Dommelen, T. D. Rybel and J. Driesen, “Technical assessment of on-load tap-changers in Flemish LV distribution grids,” in SIW13, 2013.

[31] D. Ranamuka, A. P. Agalgaonkar, and K. M. Muttaqi, “Dynamic Adjustment of OLTC Parameters using Voltage Sensitivity while utilizing DG for Volt/VAr Support,” in Integrated Power System Operations in IEEE-PES General Meeting, Washington DC, 2014.

[32] G. Nourbakhsh, B. Thomas, *et al.*, “Distribution tap changer adjustment to improve small-scale embedded generator penetration and mitigate voltage rise,” in Australasian Universities Power Engineering Conference, AUPEC 2013. Hobart, TAS, Australia2013.

[33] R. Kabiri, D. G. Holmes, and B. P. McGrath, “Voltage regulation of LV feeders with high penetration of PV distributed generation using electronic tap changing transformer,” in 24th Australasian Universities Power Engineering Conference (AUPEC) 2014.

[34] Distribution Construction Standards Handbook. Western Power; 2007.

[35] "IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems," Available: http://grouper.ieee.org/groups/scc21/1547/1547 index.html.

[36] S.K. Singh, S. kumar and S. Giri, "A Review of Voltage Control Technique of Grid Connected Distributed Generation," International Journal of Innovative Research in Science, Engineering and Technology, vol. 3, Special Issue 1, February 2014.

[37] S. Leea, Y. Chuang, J. Laia, "A novel STATCOM control scheme for the coordination with OLTC on voltage regulation," in International Journal of Smart Grid and Clean Energy, vol. 3, no. 2, April 2014.

[38] Y.P Agalgaonkar, B.C Pal, and R.A Jabr, "Distribution Voltage Control Considering the Impact of PV Generation on Tap Changers and Autonomous Regulators," in PES General Meeting | Conference & Exposition IEEE, 2014.

[39] K. Turitsyn, P. Sulc, S. Backhaus, M. Chertkov, "Local Control of Reactive Power by Distributed Photovoltaic Generators," in Smart Grid Communications (SmartGridComm), First IEEE International Conference, 2010.

[40] R. Tonkoski and L. A. C. Lopes, "Impact of Active Power Curtailment on Overvoltage Prevention and Energy Production of PV Inverters Connected to Low Voltage Residential Feeders", IEEE Power Systems. 2012.

[41] R. Tonkoski, Luiz A. C.Lopes, Tarek H. M. El-Fouly, "Coordinated active power curtailment of grid connected PV inverters for overvoltage prevention," IEEE Transactions on Sustainable Energy, vol. 2, no. 2, 2011.

[42] G. Mokhtari, A. Ghosh, G. Nourbakhsh, and G. Ledwich, "Smart Robust Resources Control in LV Network to Deal With Voltage Rise Issue," IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, VOL. 4, NO. 4, OCTOBER 2013.

[43] A. Ulinuha, M.A.S Masoum, S.M. Islam, "Optimal Scheduling of LTC and Shunt Capacitors in Large Distorted Distribution Systems Using Evolutionary-Based Algorithms, " IEEE Trans on Power Delivery, vol.23, no. 1, pp. 434-41, 2008.

[44] A. Ulinuha, M.A.S Masoum, S.M. Islam, "Hybrid Genetic-Fuzzy Algorithm for Volt/Var/THD Control of Distribution Systems with High Penetration of Nonlinear Loads," IET Trans on Generation, Transmission & Distribution, vol. 5, no. 4, pp. 425-39, 2011.

[45] Power Quality Manager, *Electricity Supply Standard*. Issue. 6, Australia, 2011.

[46] Ausgrid, *NS261 Requirement for Design Compliance Framework for Network*

Standards, 2014.

[47] Networks SP, *TS 109 EARTHING OF THE DISTRIBUTION NETWORK*, 2014.

[48] W.H. Kersting, *Distribution System Modeling and Analysis*, CRC Press, 2012.

[49] A. R. Malekpour and A. Pahwa, "Reactive power and voltage control in distribution systems with photovoltaic generation," NSF through award No. CNS-1136040, 2012.

[50] M. J. Heathcote, The J & P Transformer Book, 12nd ed. Cend., FIEE.

[51] R. C. Dugan, M". F. McGranaghan, S. Santosa, and H. W. Beaty, "*Electric Power Systems Quality*," 2nd ed. McGraw-Hill, 2002.

[52] C. Masters, "Voltage rise: The big issue when connecting embedded generation to long 11 kV overhead lines," Power Eng. J., vol. 16, no. 1, pp. 5–12, 2002.

[53] M. Baran and F. Wu, "Optimal sizing of capacitors placed on a radial distribution system," Power Delivery, IEEE Transactions on, vol. 4, no. 1, pp. 735–743, Jan 1989.

[54] ——, "Optimal capacitor placement on radial distribution systems," Power Delivery, IEEE Transactions on, vol. 4, no. 1, pp. 725–734, Jan 1989.

[55] ——, "Network reconfiguration in distribution systems for loss reduction and load balancing," Power Delivery, IEEE Transactions on, vol. 4, no. 2, pp. 1401–1407, Apr 1989.

[56] R. Baldick and F. Wu, "Efficient integer optimization algorithms for optimal coordination of capacitors and regulators," in Power Systems, IEEE Transactions on, vol. 5, no. 3, pp. 805–812, Aug 1990.

[57] Average annual and monthly sunshine duration, Bureau of Metrology, http://www.bom.gov.au/jsp/ncc/climate_averages/sunshine-hours/index.jsp

[58] T. Xu and P. C. Taylor, "Voltage control techniques for electrical distribution networks including distributed generation," IFAC, no. 1, pp. 11 967–11 971, 2008.

[59] B. O. Brewin, *et al.*, "New technologies for low voltage distribution networks," in Innovative Smart Grid Technologies (ISGT), pp. 1–8, Dec. 2011.

[60] T. Yona and N. Funabashi, "Optimal Distribution Voltage Control and Coordination with Distributed Generation," IEEE Transactions on Power Delivery, vol. 23, no. 2, 2008.

[61] J. Tani and R. Yokoyama, "Coordinated Allocation and Control of Voltage Regulators Based on Reactive Tabu Search for Distribution System," WSEAS

Transactions on Power Systems, vol. 1, no. 2, 2006.

[62] M. Saghaleini, B. Mirafzal, "Reactive Power Control in Three-Phase Grid-Connected current source boost inverter" Applied Power Electronics Conference and Exposition (APEC), Twenty-Seventh Annual IEEE 2012 , pp. 904- 910.

[63] E. Demirok, P. C. Gonz´alez, K. H. B. Frederiksen, D. Sera, P. Rodriguez and R. Teodorescu, "Local Reactive Power Control Methods for Overvoltage Prevention of Distributed Solar Inverters in Low-Voltage Grids," IEEE Journal of Photovoltaics, vol. 1, No. 2, December 2011.

[64] J. C. Vasquez, J. M. Guerrero, A. Luna, P. Rodríguez and R. Teodorescu, "Adaptive Droop Control Applied to Voltage-Source Inverters Operating in Grid-Connected and Islanded Modes," in IEEE Transaction on Industrial Electronics, vol. 56, No. 10, October 2009.

[65] K. Lemkens, F. Geth, P. Vingehoets and G Deconinck, "Reducing overvoltage problems with active power curtailment – Simulation Results," in 4th IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), Copenhagen, 2013.

[66] M. Juamperez, G. Yang and S. B. KjÆr, "Voltage regulation in LV grids by coordinated volt-var control strategies," in Power Syst. Clean Energy, 2014.

[67] P. McNutt, J. Hambrick, M. Keesee, and D. Brown, "Impact of SolarSmart Subdivisions on SMUD's Distribution System," NREL/TP-550-46093, 2009.

[68] S. Cobben, B. Gaiddon, and H. Laukamp, "Impact of Photovoltaic Generation on Power Quality in Urban Areas with High PV Population," EIE/05/171/SI2.420208, 2008.

[69] Y. Ueda, K. Kurokawa, T. Tanabe, K. Kitamura, and H. Sugihara, "Analysis Results of Output Power Loss Due to the Grid Voltage Rise in Grid-Connected Photovoltaic Power Generation Systems," IEEE Transactions on Industrial Electronics, vol. 55, pp. 2744- 2751, 2008.

[70] R. Tonkoski and L. A. C. Lopes, "Voltage Regulation in Radial Distribution Feeders with High Penetration of Photovoltaic," in IEEE Energy 2030 Conference, pp. 1-7, Atlanta, 2008.

[71] Y. Ueda, T. Oozeki, K. Kurokawa, T. ltou, K. Kitamura, Y. Miyamoto, M. Yokota, H. Sugihara, and S. Nishikawa, "Analytical Results of Output Restriction Due to the Voltage Increasing of Power Distribution Line in Grid-Connected Clustered PV Systems," in Conference Record of the Thirty-first IEEE Photovoltaic Specialists

Conference, pp. 1631-1634, 2005.

[72] F. Katiraei, K. Mauch, and L. Dignard-Bailey, "Integration of photovoltaic power systems in high-penetration clusters for distribution networks and mini-grids," in International Journal of Distributed Energy Resources, vol. 3, July-September 2007 2007.

[73] M. N. Kabir, Y. Mishra, "Utilizing Reactive Capability of PV Inverters and Battery systems to Improve Voltage Profile of a Residential Distribution Feeder," in PES General Meeting | Conference & Exposition IEEE, 2014.

[74] P. Jahangiri, and D. C. Aliprantis, "Distributed Volt/VAr Control by PV Inverters," in IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 28, NO. 3, AUGUST 2013.

[75] K. De Brabandere, A. Woyte, R. Belmans, and J. Nijs, "Prevention of Inverter Voltage Tripping in High Density PV Grids," presented at the 19th EU-PVSEC, Paris, 2004.

[76] F. Shahnia, P. Wolfs and A. Ghosh, "Voltage unbalance reduction in low voltage feeders by dynamic switching of residential customers among three phases," IEEE Trans. on Smart Grid, Vol. 5, No. 3, pp. 1318-1327, 2014.

[77] Y. Li and P. Wolfs, "Hybrid model for residential loads in a distribution system with high PV penetration," IEEE Trans. on Power Systems, Vol. 28, No. 3, pp. 3372-3379, 2013.

[78] Perth solar city annual report, 2011. http://www.westernpower.com.au/documents/psc_2012_annual_report_final_for_distribution_(lo-res_18.pdf)

APPENDIX – A

LIST OF PUBLICATION

The body of work within this thesis has been used to develop the following research outputs including publications and presentations. The thesis author is the first and primary author on all of these outputs which have been co-authored with the institutional supervisors.

- Journal Article

  Nelly Safitri, Farhad Shahnia and Mohammad A.S Masoum, "Coordination of Single-Phase Rooftop PVs in Unbalanced Three-phase Residential Feeders for Voltage Profiles Improvement," Engineers Australia Technical Journals, January 2015. (Under review).

- Conference Paper

  1. **Nelly Safitri**, Farhad Shahnia and Mohammad A.S Masoum, "Coordination of Single-Phase Rooftop PVs to Regulate Voltage Profiles of Unbalanced Residential Feeders," 24th Australasian Universities Power Engineering Conference (AUPEC) 2014, September 2014.
  2. **Nelly Safitri**, Farhad Shahnia and Mohammad A.S Masoum, "Different Techniques for Simultaneously Increasing the Penetration Level of Rooftop PVs in Residential LV Networks and Improving Voltage Profile," 6th IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC 2014), December 2014.

APPENDIX – B

VOLTAGE MAGNITUDE (PU) CASE-6

For this case, the voltage magnitudes have been captured every 15 minutes. Thus, every bus will have 96 different values of voltage magnitudes.

Vbus1	=											
	Columns	1	through	6			Columns	7	through	12		
	0.9985	0.9976	0.9973	0.999	0.9984	0.9977	0.9954	0.9935	0.9946	0.997	0.998	0.998
	0.9948	0.9969	0.997	0.9965	0.9971	0.998	0.999	0.9999	0.9994	0.9989	0.9985	0.9985
	0.993	0.9951	0.9955	0.9928	0.994	0.9955	0.9953	0.9953	0.995	0.9952	0.994	0.9951
	Columns	13	through	18			Columns	19	through	24		
	0.9971	0.9977	0.9981	0.9983	0.9982	0.9986	0.9981	0.9975	0.9962	0.996	0.996	0.9943
	0.9985	0.9958	0.9956	0.9971	0.997	0.9971	0.9976	0.9967	0.9975	0.9977	0.9974	0.9966
	0.9952	0.9944	0.995	0.9945	0.9945	0.9923	0.9931	0.9949	0.9945	0.9953	0.9956	0.9919
	Columns	25	through	30			Columns	31	through	36		
	0.9979	0.9965	0.9965	0.9973	0.999	0.9985	1.0011	0.9816	0.9989	1.0008	1.0007	1.0021
	0.9993	0.9988	0.9996	0.9988	0.998	0.9961	1	0.9736	0.9975	0.9986	1.0007	1.0019
	0.9966	0.9942	0.9933	0.9959	1.0001	1.001	1.0023	0.9781	1.0003	1.0031	1.0007	1.0024
	Columns	37	through	42			Columns	43	through	48		
	1.0004	0.9908	0.9708	0.9911	0.9796	0.9789	0.9634	0.9797	0.9912	0.9787	0.9968	0.9804
	0.9998	0.9896	0.961	0.9882	0.969	0.9773	0.9514	0.9711	0.9904	0.9725	0.9908	0.973
	1.0011	0.992	0.9707	0.994	0.9742	0.9806	0.9538	0.9738	0.992	0.9719	0.9911	0.9756
	Columns	49	through	54			Columns	55	through	60		
	0.983	0.9727	0.9883	0.9787	0.9902	0.9996	0.9896	1.0017	0.9927	0.992	1.0009	0.9984
	0.9828	0.9722	0.9779	0.9699	0.9866	0.9942	0.9806	0.9991	0.989	0.9882	0.9976	0.9961
	0.9832	0.9731	0.9838	0.9766	0.9938	1.005	0.9874	1.0043	0.9964	0.9958	1.0043	1.0007
	Columns	61	through	66			Columns	67	through	72		
	0.9985	0.9984	0.9997	0.9993	0.9989	1.0022	0.9982	0.9967	0.9954	0.9955	0.9943	0.9942
	0.9951	0.9978	0.9993	0.9982	0.9979	1.0004	0.9983	0.9974	0.9971	0.9952	0.9941	0.9909
	1.0019	0.999	1.0001	1.0004	0.9999	1.004	0.998	0.9959	0.9937	0.9958	0.9945	0.9964
	Columns	73	through	78			Columns	79	through	84		
	0.9939	0.994	0.9927	0.9926	0.9933	0.9942	0.9935	0.9936	0.9947	0.9935	0.9926	0.9935
	0.99	0.9833	0.9816	0.9872	0.9894	0.9916	0.9927	0.9929	0.9952	0.993	0.9917	0.9909
	0.995	0.9928	0.9954	0.9951	0.9961	0.9943	0.9952	0.9946	0.995	0.9965	0.9972	0.9959
	Columns	85	through	90			Columns	91	through	96		
	0.9929	0.9934	0.9924	0.9928	0.9915	0.9929	0.9928	0.9921	0.9919	0.9923	0.9937	0.9956
	0.9909	0.9904	0.9924	0.991	0.9933	0.9935	0.994	0.9962	0.9984	0.9983	0.9979	0.9975
	0.9953	0.994	0.9926	0.9915	0.9906	0.9869	0.988	0.9912	0.9928	0.9931	0.9921	0.9935

Vbus2	=											
	Columns	1	through	6			Columns	7	through	12		
	0.998	0.9964	0.996	0.9987	0.9979	0.9968	0.9927	0.9901	0.9915	0.9955	0.9973	0.9973
	0.9929	0.9953	0.9949	0.9941	0.9949	0.9967	0.9986	0.9999	0.9993	0.9982	0.9975	0.9974
	0.9894	0.9928	0.9933	0.9891	0.9907	0.9931	0.9927	0.9926	0.9923	0.9925	0.9904	0.9922
	Columns	13	through	18			Columns	19	through	24		
	0.9965	0.9974	0.9977	0.9979	0.9976	0.9986	0.9976	0.9965	0.9947	0.9945	0.9945	0.9972
	0.9972	0.994	0.9942	0.9961	0.9956	0.9958	0.9966	0.9952	0.9964	0.9966	0.9962	0.9972
	0.9925	0.9908	0.9916	0.991	0.9911	0.9873	0.9887	0.9918	0.991	0.9926	0.993	0.9972
	Columns	25	through	30			Columns	31	through	36		
	1.005	1.0001	1.0009	1.0027	1.0069	1.0046	1.0075	0.9925	1.0065	1.0063	1.0072	1.0092
	1.005	1.0001	1.0009	1.0027	1.0069	1.0046	1.0075	0.9785	1.0065	1.0063	1.0072	1.0092
	1.005	1.0001	1.0009	1.0027	1.0069	1.0046	1.0075	0.9877	1.0065	1.0063	1.0072	1.0092
	Columns	37	through	42			Columns	43	through	48		
	1.0095	1.0023	0.9837	1.0032	0.99	0.9897	0.977	0.9893	0.9998	0.9883	1.0048	0.991
	1.0095	1.0023	0.9658	1.0032	0.9718	0.9897	0.9558	0.9741	0.9998	0.9764	0.9929	0.9777
	1.0095	1.0023	0.9818	1.0032	0.9798	0.9897	0.9604	0.98	0.9998	0.9778	0.9963	0.9837
	Columns	49	through	54			Columns	55	through	60		
	0.9963	0.9863	0.9967	0.9888	1.0009	1.0071	0.9989	1.0093	1.0007	1	1.0095	1.0054
	0.9963	0.9863	0.9781	0.9721	1.0009	1.0071	0.984	1.0093	1.0007	1	1.0095	1.0054
	0.9963	0.9863	0.9901	0.9857	1.0009	1.0071	0.9961	1.0093	1.0007	1	1.0095	1.0054
	Columns	61	through	66			Columns	67	through	72		
	1.0038	1.0063	1.0075	1.0059	1.0025	1.0093	1.0017	1	0.9982	0.9988	0.9941	0.9917
	1.0038	1.0063	1.0075	1.0059	1.0025	1.0093	1.0017	1	0.9982	0.9988	0.9941	0.9869
	1.0038	1.0063	1.0075	1.0059	1.0025	1.0093	1.0017	1	0.9982	0.9988	0.9941	0.9939
	Columns	73	through	78			Columns	79	through	84		
	0.9911	0.9916	0.9895	0.9892	0.9903	0.992	0.9904	0.9906	0.9924	0.9906	0.9889	0.9909
	0.9853	0.9756	0.9721	0.9801	0.9834	0.9871	0.9879	0.9877	0.9918	0.99	0.988	0.9881
	0.9924	0.9885	0.9927	0.9921	0.9937	0.9906	0.9925	0.9916	0.9921	0.9942	0.9954	0.9925
	Columns	85	through	90			Columns	91	through	96		
	0.9903	0.9911	0.9897	0.9898	0.9873	0.9899	0.9898	0.9884	0.9876	0.9881	0.9904	0.9937
	0.9886	0.9875	0.9898	0.9872	0.9913	0.9916	0.9923	0.9955	0.9979	0.9972	0.9964	0.9956
	0.9914	0.9895	0.9876	0.986	0.9844	0.9778	0.9794	0.9849	0.9882	0.9891	0.9878	0.99

Vbus3	=											
	Columns	1	through	6			Columns	7	through	12		
	0.9974	0.9955	0.9949	0.9988	0.9976	0.9961	0.9903	0.9871	0.9886	0.9943	0.9969	0.9968
	0.9911	0.9935	0.9927	0.9917	0.9929	0.9953	0.9981	0.9998	0.9991	0.9976	0.9964	0.9964
	0.9868	0.9906	0.9913	0.9855	0.9875	0.9908	0.9901	0.9901	0.9897	0.9899	0.987	0.9895
	Columns	13	through	18			Columns	19	through	24		
	0.996	0.9973	0.9975	0.9977	0.9972	0.9982	0.9977	0.9965	0.9944	0.9939	0.9941	0.9927
	0.996	0.9922	0.9928	0.995	0.9943	0.9947	0.9954	0.9934	0.9948	0.9952	0.9945	0.9927
	0.99	0.9873	0.9883	0.9876	0.988	0.9843	0.9851	0.9888	0.9878	0.9901	0.9906	0.9927
	Columns	25	through	30			Columns	31	through	36		
	1.0035	0.9964	0.9965	1.0005	1.0072	1.0058	1.0101	1.0046	1.0079	1.0098	1.0099	1.0119
	1.0035	0.9964	0.9965	1.0005	1.0072	1.0058	1.0101	0.9795	1.0079	1.0098	1.0099	1.0119
	1.0035	0.9964	0.9965	1.0005	1.0072	1.0058	1.0101	0.9953	1.0079	1.0098	1.0099	1.0119
	Columns	37	through	42			Columns	43	through	48		
	1.0113	1.0059	0.9975	1.0062	1.0014	0.9906	0.9915	0.9996	1.0033	0.9988	1.0134	1.0025
	1.0113	1.0059	0.9663	1.0062	0.9715	0.9906	0.956	0.9738	0.9995	0.9768	0.9921	0.9785
	1.0113	1.0059	0.9916	1.0062	0.9835	0.9906	0.9648	0.9847	1.0033	0.9823	1.0004	0.9902
	Columns	49	through	54			Columns	55	through	60		
	1.0004	0.99	1.0058	0.9997	1.0059	1.0126	1.009	1.0134	1.0063	1.0051	1.0134	1.007
	1.0004	0.99	0.9753	0.9701	1.0059	1.0126	0.9837	1.0134	1.0063	1.0051	1.0134	1.007
	1.0004	0.99	0.9953	0.9935	1.0059	1.0126	1.0034	1.0134	1.0063	1.0051	1.0134	1.007
	Columns	61	through	66			Columns	67	through	72		
	1.0065	1.0062	1.01	1.0075	1.0033	1.0132	1.0008	0.9972	0.9939	0.9961	0.9904	0.9894
	1.0065	1.0062	1.01	1.0075	1.0033	1.0132	1.0008	0.9972	0.9939	0.9961	0.9904	0.9837
	1.0065	1.0062	1.01	1.0075	1.0033	1.0132	1.0008	0.9972	0.9939	0.9961	0.9904	0.9917
	Columns	73	through	78			Columns	79	through	84		
	0.9884	0.9888	0.9862	0.9861	0.9876	0.99	0.9877	0.9878	0.9903	0.9887	0.9863	0.9894
	0.9811	0.9682	0.9628	0.973	0.9774	0.9827	0.9831	0.9826	0.9883	0.9868	0.9839	0.985
	0.9903	0.9867	0.9912	0.9893	0.9917	0.9872	0.9901	0.9888	0.9896	0.9921	0.9939	0.9894
	Columns	85	through	90			Columns	91	through	96		
	0.9888	0.9898	0.988	0.9879	0.984	0.9872	0.9873	0.9856	0.9841	0.9849	0.9887	0.9925
	0.9859	0.9842	0.9868	0.983	0.989	0.9895	0.9905	0.9945	0.9972	0.9958	0.9942	0.9935
	0.9878	0.9853	0.9829	0.9808	0.9785	0.971	0.9726	0.9791	0.9839	0.9855	0.9842	0.987

Vbus4	=											
	Columns	1	through	6			Columns	7	through	12		
	0.9971	0.995	0.9942	0.9991	0.9977	0.9958	0.9883	0.9844	0.986	0.9931	0.9967	0.9965
	0.9894	0.9919	0.9905	0.9893	0.9907	0.9939	0.9976	0.9997	0.9989	0.9969	0.9953	0.9954
	0.9845	0.9886	0.9895	0.9822	0.9846	0.9886	0.9878	0.9877	0.9872	0.9875	0.9838	0.9869
	Columns	13	through	18			Columns	19	through	24		
	0.9957	0.9973	0.9976	0.9977	0.9969	0.9979	0.998	0.9967	0.9941	0.9936	0.9938	0.9959
	0.9948	0.9904	0.9914	0.994	0.993	0.9935	0.9943	0.9916	0.9933	0.9938	0.993	0.9899
	0.9876	0.9842	0.9853	0.9843	0.9851	0.9815	0.9817	0.986	0.9849	0.9877	0.9884	0.9929
	Columns	25	through	30			Columns	31	through	36		
	1.0099	1.0002	1.002	1.0066	1.0142	1.0108	1.015	1.0132	1.014	1.0141	1.0148	1.0169
	1.002	0.9949	0.995	0.9983	1.006	1.004	1.0099	0.9809	1.0051	1.0083	1.0101	1.0132
	1.0059	0.9976	0.9985	1.0025	1.0101	1.0074	1.0124	1.0028	1.0095	1.0112	1.0124	1.0151
	Columns	37	through	42			Columns	43	through	48		
	1.0176	1.0139	1.0074	1.0155	1.01	0.9989	1.0024	1.0069	1.0096	1.0065	1.0192	1.0107
	1.0125	1.007	0.9677	1.0061	0.9718	0.9899	0.9576	0.9746	1.0005	0.978	0.9916	0.98
	1.0151	1.0104	1.0015	1.0108	0.9882	0.9944	0.9699	0.9898	1.0071	0.9875	1.0049	0.9979
	Columns	49	through	54			Columns	55	through	60		
	1.0109	1.001	1.0125	1.0076	1.0142	1.0183	1.0161	1.0191	1.012	1.0108	1.0198	1.0125
	1.0014	0.991	0.9735	0.9696	1.0048	1.0106	0.9843	1.0137	1.007	1.0053	1.013	1.0057
	1.0062	0.996	1.0012	1.0021	1.0095	1.0144	1.0108	1.0164	1.0095	1.008	1.0164	1.0091
	Columns	61	through	66			Columns	67	through	72		
	1.0104	1.0124	1.0159	1.0128	1.0066	1.0191	1.0037	1.0001	0.9965	0.9995	0.9911	0.9874
	1.0051	1.0059	1.0101	1.0076	1.0027	1.0134	0.9994	0.9952	0.9918	0.9938	0.9882	0.9804
	1.0077	1.0092	1.013	1.0102	1.0047	1.0162	1.0016	0.9977	0.9941	0.9967	0.9897	0.9897
	Columns	73	through	78			Columns	79	through	84		
	0.9862	0.9862	0.9832	0.9832	0.9851	0.9881	0.9852	0.9851	0.9884	0.9869	0.9844	0.9881
	0.9769	0.961	0.9535	0.966	0.9715	0.9784	0.9784	0.9776	0.985	0.9836	0.9798	0.9818
	0.9885	0.9852	0.9898	0.9868	0.99	0.9843	0.988	0.9865	0.9875	0.9903	0.9927	0.9866
	Columns	85	through	90			Columns	91	through	96		
	0.9875	0.9889	0.987	0.9862	0.9808	0.9847	0.9853	0.9833	0.9812	0.9822	0.9876	0.9919
	0.9832	0.9809	0.9836	0.9788	0.9869	0.9875	0.9886	0.9935	0.9964	0.9944	0.992	0.9912
	0.9846	0.9814	0.9786	0.976	0.973	0.9645	0.9663	0.9737	0.9798	0.9821	0.9807	0.9844

Vbus5	=											
	Columns	1	through	6			Columns	7	through	12		
	0.997	0.9945	0.9937	0.9991	0.9978	0.9957	0.9866	0.9819	0.9837	0.9922	0.9963	0.9963
	0.9878	0.9903	0.9886	0.9872	0.9888	0.9925	0.9973	0.9997	0.9987	0.9964	0.9945	0.9945
	0.9822	0.9867	0.9878	0.9802	0.9824	0.9866	0.9856	0.9855	0.9849	0.9853	0.9819	0.985
	Columns	13	through	18			Columns	19	through	24		
	0.9956	0.9975	0.9978	0.998	0.9968	0.9978	0.9985	0.9971	0.9941	0.9934	0.9937	0.9873
	0.9938	0.989	0.9901	0.993	0.992	0.9925	0.9933	0.9901	0.9919	0.9925	0.9917	0.9873
	0.9855	0.9811	0.9825	0.9814	0.9825	0.979	0.9785	0.9833	0.9823	0.9856	0.9865	0.9873
	Columns	25	through	30			Columns	31	through	36		
	1.0006	0.9935	0.9935	0.9961	1.0046	1.0019	1.0095	1.0226	1.0024	1.0061	1.0097	1.0141
	1.0006	0.9935	0.9935	0.9961	1.0046	1.0019	1.0095	0.9822	1.0024	1.0061	1.0097	1.0141
	1.0006	0.9935	0.9935	0.9961	1.0046	1.0019	1.0095	1.0093	1.0024	1.0061	1.0097	1.0141
	Columns	37	through	42			Columns	43	through	48		
	1.0135	1.0077	1.0188	1.0055	1.0202	0.9884	1.0149	1.0162	1.0008	1.0163	1.0274	1.0204
	1.0135	1.0077	0.9686	1.0055	0.9715	0.9884	0.9585	0.9746	1.0008	0.9786	0.9904	0.9815
	1.0135	1.0077	1.01	1.0055	0.9918	0.9884	0.9748	0.9946	1.0008	0.9923	1.0085	1.0042
	Columns	49	through	54			Columns	55	through	60		
	1.0218	0.9917	1.0202	1.0167	1.004	1.0089	1.0245	1.0129	1.0064	1.0042	1.0118	1.0046
	1.0023	0.9917	0.972	0.9695	1.004	1.0089	0.9844	1.0129	1.0064	1.0042	1.0118	1.0046
	1.0023	0.9917	1.006	1.0091	1.004	1.0089	1.0171	1.0129	1.0064	1.0042	1.0118	1.0046
	Columns	61	through	66			Columns	67	through	72		
	1.0041	1.0054	1.01	1.0074	1.002	1.0133	0.9981	0.9933	0.9898	0.9917	0.9864	0.9856
	1.0041	1.0054	1.01	1.0074	1.002	1.0133	0.9981	0.9933	0.9898	0.9917	0.9864	0.9777
	1.0041	1.0054	1.01	1.0074	1.002	1.0133	0.9981	0.9933	0.9898	0.9917	0.9864	0.988
	Columns	73	through	78			Columns	79	through	84		
	0.9841	0.9834	0.98	0.9799	0.9825	0.9864	0.9827	0.9826	0.9866	0.985	0.9825	0.9871
	0.9737	0.9547	0.9452	0.9601	0.9665	0.9747	0.9742	0.9728	0.9819	0.9809	0.9759	0.9791
	0.9872	0.9853	0.9905	0.9866	0.9896	0.982	0.9867	0.985	0.9862	0.9895	0.9922	0.9841
	Columns	85	through	90			Columns	91	through	96		
	0.986	0.9874	0.9857	0.984	0.9784	0.9825	0.983	0.9811	0.9787	0.98	0.9867	0.9915
	0.9812	0.9784	0.981	0.9754	0.9849	0.986	0.987	0.9926	0.9957	0.993	0.99	0.989
	0.9828	0.9802	0.9766	0.9742	0.9699	0.9612	0.9635	0.9705	0.977	0.9797	0.9789	0.983

Vbus6	=											
	Columns	1	through	6			Columns	7	through	12		
	0.9969	0.9942	0.9933	0.9993	0.998	0.9957	0.9849	0.9796	0.9815	0.9915	0.996	0.9962
	0.9864	0.9888	0.9869	0.9855	0.9871	0.9914	0.9972	1	0.9986	0.996	0.9939	0.9936
	0.98	0.9849	0.9862	0.978	0.9803	0.9846	0.9835	0.9833	0.9828	0.9833	0.9802	0.9832
	Columns	13	through	18			Columns	19	through	24		
	0.9956	0.9978	0.9981	0.9982	0.9968	0.9978	0.9989	0.9975	0.9941	0.9932	0.9937	0.9841
	0.9929	0.9878	0.9889	0.9922	0.9912	0.9917	0.9924	0.9888	0.9908	0.9916	0.9907	0.9841
	0.9834	0.9782	0.9798	0.9787	0.9799	0.9765	0.9755	0.9807	0.9797	0.9834	0.9845	0.9841
	Columns	25	through	30			Columns	31	through	36		
	0.9984	0.9898	0.9885	0.9938	1.0034	1.0012	1.0098	1.0317	1.0029	1.0078	1.01	1.0145
	0.9984	0.9898	0.9885	0.9938	1.0034	1.0012	1.0098	0.9838	1.0029	1.0078	1.01	1.0145
	0.9984	0.9898	0.9885	0.9938	1.0034	1.0012	1.0098	1.0122	1.0029	1.0078	1.01	1.0145
	Columns	37	through	42			Columns	43	through	48		
	1.0136	1.0085	1.0301	1.0056	1.0306	0.9865	1.0276	1.0261	1.0016	1.0264	1.0359	1.0307
	1.0136	1.0085	0.9695	1.0056	0.9719	0.9865	0.9606	0.9758	1.0016	0.9804	0.9905	0.9839
	1.0136	1.0085	1.014	1.0056	0.9917	0.9865	0.9759	0.9956	1.0016	0.9926	1.0083	1.006
	Columns	49	through	54			Columns	55	through	60		
	1.0324	0.9916	1.0285	1.0269	1.0049	1.0106	1.0334	1.0142	1.0088	1.0059	1.0131	1.0042
	1.0031	0.9916	0.9713	0.9704	1.0049	1.0106	0.9847	1.0142	1.0088	1.0059	1.0131	1.0042
	1.0031	0.9916	1.0069	1.0114	1.0049	1.0106	1.0198	1.0142	1.0088	1.0059	1.0131	1.0042
	Columns	61	through	66			Columns	67	through	72		
	1.0043	1.0039	1.0102	1.007	1.002	1.015	0.9967	0.9904	0.9859	0.9889	0.9835	0.9841
	1.0043	1.0039	1.0102	1.007	1.002	1.015	0.9967	0.9904	0.9859	0.9889	0.9835	0.9766
	1.0043	1.0039	1.0102	1.007	1.002	1.015	0.9967	0.9904	0.9859	0.9889	0.9835	0.986
	Columns	73	through	78			Columns	79	through	84		
	0.9822	0.9807	0.9769	0.9768	0.9801	0.9843	0.9803	0.9807	0.985	0.9833	0.9811	0.9864
	0.9721	0.9497	0.9385	0.9559	0.9629	0.9721	0.9725	0.9713	0.9802	0.979	0.9746	0.9779
	0.9856	0.9853	0.991	0.9861	0.989	0.981	0.9853	0.9824	0.9846	0.9886	0.9908	0.9814
	Columns	85	through	90			Columns	91	through	96		
	0.9848	0.9862	0.9847	0.982	0.9761	0.9806	0.9811	0.9791	0.9764	0.9781	0.9859	0.9914
	0.9799	0.9774	0.98	0.9729	0.9835	0.9855	0.9869	0.9927	0.9959	0.9922	0.9886	0.9874
	0.9809	0.9786	0.9742	0.9722	0.9668	0.9575	0.9602	0.967	0.9739	0.9771	0.9768	0.9814

Vbus7	=											
	Columns	1	through	6			Columns	7	through	12		
	0.997	0.9941	0.9931	0.9995	0.9983	0.9958	0.9833	0.9774	0.9797	0.991	0.9958	0.9962
	0.9859	0.9883	0.9864	0.9848	0.9865	0.9909	0.9975	1.0005	0.9989	0.9958	0.9936	0.9932
	0.978	0.9831	0.9844	0.9759	0.9782	0.9828	0.9816	0.9814	0.9808	0.9815	0.9786	0.9816
	Columns	13	through	18			Columns	19	through	24		
	0.9956	0.9982	0.9985	0.9985	0.9969	0.9979	0.9995	0.998	0.9943	0.9932	0.9938	0.9823
	0.9924	0.987	0.9882	0.9918	0.9907	0.9912	0.9918	0.9879	0.99	0.991	0.9901	0.9833
	0.9816	0.9755	0.9773	0.9763	0.9777	0.9743	0.9727	0.9783	0.9774	0.9815	0.9828	0.9812
	Columns	25	through	30			Columns	31	through	36		
	0.9974	0.9877	0.9856	0.992	1.0026	1.0008	1.0104	1.0367	1.0024	1.0078	1.0101	1.0151
	0.9979	0.9889	0.9874	0.9921	1.0025	1.0005	1.0098	0.9846	1.0001	1.0049	1.0092	1.0145
	0.9968	0.9866	0.9839	0.992	1.0028	1.0011	1.0109	1.0159	1.0047	1.0106	1.0111	1.0157
	Columns	37	through	42			Columns	43	through	48		
	1.0141	1.0093	1.037	1.0057	1.0373	0.9854	1.0362	1.033	1.0027	1.0325	1.041	1.0369
	1.0137	1.0087	0.9697	1.0051	0.9725	0.9857	0.9621	0.9766	1.0021	0.9814	0.9907	0.9861
	1.0146	1.01	1.0188	1.0064	0.992	0.9852	0.9778	0.9973	1.0034	0.9955	1.0107	1.0092
	Columns	49	through	54			Columns	55	through	60		
	1.0388	0.9934	1.0334	1.0332	1.0056	1.0114	1.0385	1.0148	1.01	1.0066	1.0137	1.004
	1.0042	0.9924	0.9706	0.9709	1.0042	1.0094	0.9843	1.0129	1.0077	1.0046	1.0118	1.0034
	1.0054	0.9945	1.0094	1.0146	1.0069	1.0133	1.0237	1.0166	1.0123	1.0085	1.0155	1.0046
	Columns	61	through	66			Columns	67	through	72		
	1.0046	1.0033	1.0106	1.007	1.0017	1.016	0.9958	0.9884	0.9834	0.987	0.9815	0.9833
	1.0039	1.0033	1.0101	1.0065	1.0008	1.0147	0.9957	0.9889	0.9843	0.9874	0.982	0.9754
	1.0053	1.0034	1.0111	1.0074	1.0025	1.0174	0.9959	0.9879	0.9825	0.9865	0.981	0.9844
	Columns	73	through	78			Columns	79	through	84		
	0.9812	0.9791	0.9749	0.9748	0.9786	0.9831	0.9789	0.9791	0.9836	0.9817	0.9798	0.9857
	0.9703	0.9456	0.9332	0.9519	0.9594	0.9696	0.9706	0.9699	0.9787	0.9774	0.9734	0.9768
	0.9844	0.9852	0.9913	0.9859	0.9888	0.9805	0.9844	0.9802	0.9834	0.9882	0.9899	0.9792
	Columns	85	through	90			Columns	91	through	96		
	0.9837	0.9851	0.9837	0.98	0.974	0.9787	0.979	0.9772	0.9742	0.9762	0.9854	0.9914
	0.979	0.9766	0.9791	0.9706	0.9825	0.9855	0.9869	0.9929	0.9963	0.9921	0.988	0.9867
	0.9795	0.9774	0.9723	0.9707	0.964	0.9543	0.9574	0.964	0.9712	0.9749	0.9749	0.9799

Vbus8	=											
	Columns	1	through	6			Columns	7	through	12		
	0.9971	0.9944	0.9932	0.9999	0.9988	0.9961	0.982	0.9755	0.9779	0.9906	0.996	0.9965
	0.9857	0.988	0.9859	0.9843	0.986	0.9906	0.9979	1.0012	0.9994	0.9959	0.9934	0.9929
	0.9762	0.9814	0.9827	0.974	0.9763	0.9812	0.9797	0.9795	0.9789	0.9798	0.9771	0.9801
	Columns	13	through	18			Columns	19	through	24		
	0.9959	0.9989	0.999	0.9991	0.9974	0.9983	1.0003	0.9986	0.9948	0.9934	0.994	0.987
	0.9922	0.9865	0.9878	0.9916	0.9904	0.9908	0.9914	0.9876	0.9896	0.9907	0.9899	0.987
	0.9799	0.9728	0.9749	0.9741	0.9755	0.9723	0.97	0.9759	0.9752	0.9798	0.9812	0.987
	Columns	25	through	30			Columns	31	through	36		
	1.0057	0.9931	0.9945	1.0013	1.0127	1.0094	1.0174	1.0411	1.012	1.0157	1.0172	1.0209
	1.0057	0.9931	0.9945	1.0013	1.0127	1.0094	1.0174	0.9876	1.012	1.0157	1.0172	1.0209
	1.0057	0.9931	0.9945	1.0013	1.0127	1.0094	1.0174	1.0188	1.012	1.0157	1.0172	1.0209
	Columns	37	through	42			Columns	43	through	48		
	1.0205	1.0178	1.0422	1.0181	1.0426	1.0014	1.0428	1.0381	1.0053	1.0373	1.0449	1.0416
	1.0205	1.0178	0.9722	1.0181	0.9747	1.0014	0.9652	0.979	1.0053	0.9838	0.9924	0.9897
	1.0205	1.0178	1.0228	1.0181	0.9923	1.0014	0.9796	0.999	1.0053	0.9979	1.013	1.0123
	Columns	49	through	54			Columns	55	through	60		
	1.0437	0.9986	1.0374	1.038	1.0168	1.0211	1.0427	1.0258	1.0212	1.0179	1.0231	1.0117
	1.0257	0.9986	0.9727	0.9737	1.0168	1.0211	0.987	1.0258	1.0212	1.0179	1.0231	1.0117
	1.0077	0.9986	1.0111	1.0175	1.0168	1.0211	1.0262	1.0258	1.0212	1.0179	1.0231	1.0117
	Columns	61	through	66			Columns	67	through	72		
	1.0106	1.0113	1.0184	1.0146	1.0066	1.0239	1.0002	0.9928	0.9872	0.9924	0.9832	0.9833
	1.0106	1.0113	1.0184	1.0146	1.0066	1.0239	1.0002	0.9928	0.9872	0.9924	0.9832	0.9753
	1.0106	1.0113	1.0184	1.0146	1.0066	1.0239	1.0002	0.9928	0.9872	0.9924	0.9832	0.9826
	Columns	73	through	78			Columns	79	through	84		
	0.9808	0.9783	0.9738	0.9736	0.9777	0.9823	0.9779	0.9779	0.9826	0.9806	0.9788	0.9853
	0.9697	0.9442	0.9313	0.9511	0.9577	0.9683	0.97	0.9697	0.9783	0.9763	0.9728	0.9762
	0.9828	0.9841	0.9905	0.9846	0.988	0.9796	0.9832	0.9779	0.9821	0.9877	0.989	0.977
	Columns	85	through	90			Columns	91	through	96		
	0.983	0.9845	0.9832	0.9783	0.9722	0.9772	0.9774	0.9756	0.9724	0.9747	0.9851	0.9916
	0.9786	0.9762	0.9789	0.9691	0.9821	0.9859	0.9874	0.9935	0.997	0.9926	0.9879	0.9865
	0.978	0.9762	0.9704	0.9692	0.9615	0.9513	0.9548	0.9614	0.9689	0.9725	0.9731	0.9785

Vbus9	=											
	Columns	1	through	6			Columns	7	through	12		
	0.997	0.9943	0.9931	0.9999	0.9988	0.9962	0.9819	0.9754	0.978	0.9906	0.996	0.9965
	0.9857	0.9878	0.9856	0.9841	0.9858	0.9904	0.9978	1.001	0.9992	0.9958	0.9933	0.9928
	0.9755	0.9809	0.9822	0.9733	0.9757	0.9805	0.979	0.9789	0.9782	0.9791	0.9765	0.9795
	Columns	13	through	18			Columns	19	through	24		
	0.9959	0.9994	0.9994	0.9993	0.9977	0.9985	1.0005	0.9989	0.995	0.9934	0.9939	0.9853
	0.9921	0.9862	0.9875	0.9914	0.9903	0.9907	0.9913	0.9874	0.9893	0.9905	0.9897	0.9853
	0.9791	0.9711	0.9734	0.9728	0.9743	0.9711	0.9687	0.9748	0.974	0.9791	0.9805	0.9853
	Columns	25	through	30			Columns	31	through	36		
	1.0045	0.9907	0.9918	0.9997	1.0119	1.0094	1.0182	1.0452	1.0133	1.0177	1.0185	1.0219
	1.0045	0.9907	0.9918	0.9997	1.0119	1.0094	1.0182	0.9892	1.0133	1.0177	1.0185	1.0219
	1.0045	0.9907	0.9918	0.9997	1.0119	1.0094	1.0182	1.0207	1.0133	1.0177	1.0185	1.0219
	Columns	37	through	42			Columns	43	through	48		
	1.0209	1.0184	1.0467	1.0182	1.0471	1.0013	1.0484	1.0425	1.0073	1.0416	1.0485	1.0461
	1.0209	1.0184	0.9746	1.0182	0.9759	1.0013	0.967	0.9805	1.0073	0.9852	0.9929	0.9917
	1.0209	1.0184	1.0249	1.0182	0.9919	1.0013	0.9806	0.9999	1.0073	0.9997	1.0149	1.0145
	Columns	49	through	54			Columns	55	through	60		
	1.0477	1.0006	1.0413	1.0427	1.0188	1.0227	1.0461	1.0273	1.0228	1.0185	1.0238	1.0112
	1.0096	1.0006	0.9736	0.9748	1.0188	1.0227	0.9887	1.0273	1.0228	1.0185	1.0238	1.0112
	1.0096	1.0006	1.0124	1.0194	1.0188	1.0227	1.0283	1.0273	1.0228	1.0185	1.0238	1.0112
	Columns	61	through	66			Columns	67	through	72		
	1.011	1.0108	1.0189	1.0144	1.0066	1.0251	0.9994	0.9906	0.9841	0.9901	0.9816	0.9832
	1.011	1.0108	1.0189	1.0144	1.0066	1.0251	0.9994	0.9906	0.9841	0.9901	0.9816	0.9753
	1.011	1.0108	1.0189	1.0144	1.0066	1.0251	0.9994	0.9906	0.9841	0.9901	0.9816	0.9818
	Columns	73	through	78			Columns	79	through	84		
	0.9805	0.9777	0.9731	0.9728	0.9773	0.9818	0.9773	0.9776	0.9821	0.98	0.9782	0.985
	0.9696	0.9442	0.9315	0.9513	0.9577	0.9681	0.9698	0.9695	0.978	0.976	0.9726	0.9759
	0.982	0.9834	0.9897	0.9838	0.9873	0.979	0.9824	0.976	0.9811	0.9871	0.9883	0.9753
	Columns	85	through	90			Columns	91	through	96		
	0.9825	0.9842	0.983	0.9782	0.9723	0.9776	0.9778	0.976	0.9727	0.9749	0.9852	0.9917
	0.9783	0.9759	0.9787	0.967	0.9809	0.9856	0.9871	0.9933	0.9968	0.9923	0.9878	0.9863
	0.9771	0.9757	0.9691	0.9685	0.9604	0.9499	0.9533	0.9599	0.9675	0.9713	0.9722	0.978

Vbus10	=											
	Columns	1	through	6			Columns	7	through	12		
	0.9971	0.9942	0.9931	1	0.9989	0.9963	0.982	0.9754	0.978	0.9907	0.9961	0.9965
	0.9857	0.9878	0.9856	0.9841	0.9858	0.9903	0.9978	1.0011	0.9992	0.9958	0.9932	0.9928
	0.9751	0.9806	0.9819	0.9729	0.9755	0.9802	0.9786	0.9786	0.9779	0.9788	0.9763	0.9793
	Columns	13	through	18			Columns	19	through	24		
	0.9959	0.9994	0.9994	0.9994	0.9977	0.9985	1.0006	0.9989	0.9951	0.9934	0.994	0.9849
	0.9921	0.9862	0.9875	0.9914	0.9903	0.9907	0.9913	0.9873	0.9893	0.9905	0.9897	0.9849
	0.9788	0.9708	0.9731	0.9725	0.9741	0.9708	0.9684	0.9745	0.9738	0.9788	0.9802	0.9849
	Columns	25	through	30			Columns	31	through	36		
	1.0039	0.99	0.9909	0.9989	1.011	1.009	1.0179	1.0462	1.0129	1.0173	1.0181	1.0215
	1.0039	0.99	0.9909	0.9989	1.011	1.009	1.0179	0.9887	1.0129	1.0173	1.0181	1.0215
	1.0039	0.99	0.9909	0.9989	1.011	1.009	1.0179	1.0243	1.0129	1.0173	1.0181	1.0215
	Columns	37	through	42			Columns	43	through	48		
	1.0203	1.0176	1.0475	1.0178	1.0481	1.0006	1.0495	1.0435	1.0068	1.0427	1.0495	1.0471
	1.0203	1.0176	0.9742	1.0178	0.9754	1.0006	0.9665	0.98	1.0068	0.9847	0.9924	0.9911
	1.0203	1.0176	1.0293	1.0178	0.9951	1.0006	0.9854	1.0032	1.0068	1.0032	1.0181	1.0187
	Columns	49	through	54			Columns	55	through	60		
	1.0092	1.0001	1.0423	1.044	1.0184	1.0225	1.0466	1.0269	1.0224	1.0181	1.0235	1.0109
	1.0092	1.0001	0.9732	0.9742	1.0184	1.0225	0.9885	1.0269	1.0224	1.0181	1.0235	1.0109
	1.0092	1.0001	1.0155	1.0231	1.0184	1.0225	1.0321	1.0269	1.0224	1.0181	1.0235	1.0109
	Columns	61	through	66			Columns	67	through	72		
	1.0108	1.0107	1.0186	1.0141	1.0064	1.0248	0.999	0.9899	0.9832	0.9893	0.9812	0.9832
	1.0108	1.0107	1.0186	1.0141	1.0064	1.0248	0.999	0.9899	0.9832	0.9893	0.9812	0.9753
	1.0108	1.0107	1.0186	1.0141	1.0064	1.0248	0.999	0.9899	0.9832	0.9893	0.9812	0.9812
	Columns	73	through	78			Columns	79	through	84		
	0.9802	0.9773	0.9726	0.9723	0.977	0.9816	0.977	0.9777	0.982	0.9797	0.978	0.9851
	0.9697	0.9444	0.9317	0.9515	0.9578	0.9683	0.9699	0.9695	0.9781	0.9761	0.9727	0.9759
	0.9817	0.983	0.9893	0.9835	0.9868	0.9785	0.9819	0.9743	0.9801	0.9867	0.9877	0.9738
	Columns	85	through	90			Columns	91	through	96		
	0.9821	0.9838	0.9826	0.9778	0.9722	0.9776	0.9778	0.9761	0.9726	0.9749	0.9852	0.9917
	0.9784	0.9761	0.9788	0.9651	0.9801	0.9856	0.9871	0.9932	0.9968	0.9923	0.9878	0.9862
	0.9764	0.9754	0.9688	0.969	0.9604	0.9496	0.9531	0.9596	0.9673	0.971	0.9719	0.9779