An Investigation of Innovative Voltage Control Approaches to Increase Rooftop PV Penetration

by

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Author’s Declaration

I declare that this thesis is my own account of my research and contains as its main content work which has not previously been submitted for a degree at any tertiary education institution.

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Date: .................................

Word account for all parts of the thesis (excluding references and appendices): 13,988
Abstract

In Western Australia, steady increases in rooftop photovoltaic (PV) systems are mainly caused by the continued decrease in the cost of solar PV systems. The high penetration of PV systems will cause increasing reverse power to be injected into grids. As a result, the distribution network will face major voltage rise challenges. This issue has a negative influence on the reliability and security of the power network operation. Therefore, it is necessary to investigate methods to mitigate voltage rise to enhance the penetration of rooftop PV systems.

This study evaluates the effectiveness of feasible solutions for voltage management through simulation studies using the DIgSILENT PowerFactory software. These solutions draw on control means provided by utility operated equipment only or in combination with utility and prosumer operated equipment. In this project, the primary strategy used to mitigate voltage rise was the use of on-load voltage regulation transformers (OL-VRDTs) with and without the application of the line drop compensation (LDC) on a 22kV/415V distribution network. This study also examined the combination methods between the OL-VRDTs with and without LDC and prosumers’ reactive power controls in their PV inverters (fixed power factor controller or volt-var response control Q(V)).

The results showed that the implementation of the OL-VRDTs with LDC was the best utility approach to mitigate voltage rise. However, the success of this method depends on the selection of the set-point voltage of the OLTCs and the line drop compensation parameters. Furthermore, the voltage rise mitigation capability of the sole OL-VRDTs-based methods can be improved when combined with the reactive power controls of PV inverters. This is because reactive power controllers absorb additional reactive power from the grid to reduce voltage rise. However, this may require additional investment by utilities to inject more reactive
power into their grids. The Q(V) controller has a lower Q demand than the fixed power factor controller and is hence the preferred prosumer method. However, the most advanced prosumer method is fulltime Q(V) control, which is independent of solar PV generation. In addition, it was shown that both OL-VRDT-based voltage control and fulltime Q(V) control can reduce voltage variations and increase the load carrying capacity of the LV feeder.
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**List of Abbreviations (Glossary is Located after References)**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
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<tr>
<td>DC</td>
<td>Direct current</td>
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<tr>
<td>DOD</td>
<td>Depth of discharge</td>
</tr>
<tr>
<td>DSO</td>
<td>Distributed system operator</td>
</tr>
<tr>
<td>FT-DT</td>
<td>Fixed-tap Distribution Transformer</td>
</tr>
<tr>
<td>HV</td>
<td>High Voltage – AC voltages above 33kV in WA grid</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IES</td>
<td>Inverter Energy Systems</td>
</tr>
<tr>
<td>LDC</td>
<td>Line Drop Compensation</td>
</tr>
<tr>
<td>LV</td>
<td>Low Voltage - AC voltages up to 1kV, so includes 415V</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracker</td>
</tr>
<tr>
<td>MR</td>
<td>Maschinenfabrik Reinhausen</td>
</tr>
<tr>
<td>MV</td>
<td>Medium voltage - AC voltages above 1kV and up to 33kV in WA grid. Note that Western Power refers to this voltage range as HV</td>
</tr>
<tr>
<td>OLTC</td>
<td>On-load Tap Changer</td>
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<tr>
<td>OL-VRDT</td>
<td>On-load Voltage Regulation Distribution Transformer</td>
</tr>
<tr>
<td>PCC</td>
<td>Point of common coupling</td>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
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<tr>
<td>STATCOM</td>
<td>Static Synchronous Compensator</td>
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<tr>
<td>SWIS</td>
<td>South West Interconnected System</td>
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<tr>
<td>WA</td>
<td>Western Australia</td>
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<tr>
<td>WP</td>
<td>Western Power</td>
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Chapter 1: Introduction

1.1 Project Motivation

Energy sources for electricity generation are transitioning from fossil fuels to renewable energy—mainly solar and wind power. The scale-up of production and decreasing cost of solar photovoltaic (PV) systems make solar energy an attractive source for electricity production [1]. PV rooftop systems are shifting the ownership of electricity production from utilities to prosumers\(^1\), which means that an increasing number of prosumers will generate their own electricity to satisfy the household load through installing rooftop solar PV systems. Currently, ‘behind-the-meter’ batteries paired with rooftop PV systems are receiving attention and encouraging further expansion of PV penetration\(^2\) [1] because of the benefits of battery storage systems in discharging the stored solar energy to reduce the peak load demand at night [1].

However, with the continuing increase of rooftop solar PV generation, conventional networks will face a series of technical challenges—particularly voltage rise during periods of high solar generation and low household electricity demand [4]. Voltage rise on grids is caused by reverse power flow [4]. Traditional networks are designed for unidirectional power flow, where electricity is transmitted from power plants on high voltage (HV) transmission lines and then via medium voltage (MV) networks to consumers on the low voltage (LV) networks. A high penetration of rooftop solar PV systems can cause power flow in the reverse direction in conventional networks [4] because the power generated from PV systems that cannot be consumed by loads is injected into grids from LV networks to MV and HV networks [4].

\(^1\) Owners of distributed energy system who not only consume energy but also provide excess energy to the grid and/or to other consumers [2]

\(^2\) “The ratio of peak PV power to the peak load apparent power on the feeder” [3]
voltage rise has a negative influence on the functioning of network equipment and household appliances [5]. For example, the power consumption of appliances increases, and inverter energy systems (IES) are likely to be disconnected from grids [5]. The conventional method to mitigate voltage rise is grid reinforcement, which is achieved by rearranging transformers or line augmentations [5]. However, this strategy is costly for utilities and is not used until other methods have been exhausted to alleviate this issue [3]. Therefore, before solar becomes the leading energy source for electricity, it is necessary to investigate feasible methods to alleviate voltage rise on grids without needing to use grid reinforcement.

Western Power (WP), the main electricity delivery company in Western Australia [6], has supported this project by providing the details from a representative 22 kV feeder, which was used as the MV distribution network to evaluate the different voltage regulation strategies employed in this study.

1.2 Aims and Objectives

Although approaches to manage the voltage levels in high penetration of PV networks have been widely investigated, with the development of technologies and improvement of devices, new technical solutions are being explored for grid planning and operation. Therefore, this study aimed to explore advanced methods to reduce voltage rise and allow an increase in rooftop solar PV systems, based on data from a representative 22kV feeder network provided by WP in Western Australia. This process required:

- conducting a literature review to summarise the methods that have been previously studied for mitigating voltage rise, and determining the research gaps in this field,
- identifying possible new methods and the feasible combination of these methods of voltage rise mitigation for this study,
• modelling a representative LV distribution network connected to the end of the 22 kV WP feeder by using the DIgSILENT PowerFactory 2017 software package, and
• undertaking load flow analyses using the DIgSILENT PowerFactory 2017 to evaluate the voltage profiles, power flows and grid losses resulting from implementing the selected approaches on the representative feeder.

In addition, this project is an extension study of a previous thesis [7] that investigated. Hence, it is worth exploring the effectiveness of the selected focused voltage management methods in the previously studied power network, and determining the influence of different grid characteristics on voltage profiles through a comparative analysis.

1.3 Thesis Structure

There are six chapters in this thesis, as follows. Chapter 2 describes the characteristics of solar energy in Western Australia (WA), and introduces the current status and future development estimation of rooftop PV installations. Chapter 3 is a literature review that provides an overview of the state-of-the-art approaches for reducing voltage rise. Chapter 4 is the methodology section, and discusses the selected methods to mitigate voltage rise, as well as describing related simulation methods. Chapter 5 is a comparative study that evaluates the effectiveness of the chosen focused methods in the previously studied power network [7]. Chapter 6 introduces a more representative WA MV network and models the new LV power network using related electronic elements. Chapter 7 contains load flow simulations for each determined method, under different PV penetration levels in the representative network, and presents and discusses the simulation results that relate to voltage management. Finally, Chapter 8 concludes the thesis by listing the key findings of this project and presenting suggestions for further study.
Chapter 2: Solar and Rooftop PV Systems in the South West Interconnected System

To implement advanced voltage management methods to mitigate voltage rise in the network provided by WP, it is necessary to acknowledge the development of solar and rooftop PV systems in the South West Interconnected System (SWIS) [6]. SWIS refers to electricity generators in the South West Interconnected Network formed by WP in WA [6].

2.1 Solar Resources in SWIS

Solar PV systems convert solar energy to electricity through PV cells and inverters [8]. Although the electricity yield of a PV system is relevant to the rated power and technologies of PV modules, it is most dependent on the amount of solar radiation falling on the PV systems [8].

Australia is a country with an excellent solar energy source [9]. Hence, it is worth installing PV systems to employ the abundant solar energy source in Australia [9]. Figure 2.1 presents the horizontal global daily solar radiation in Perth, WA, for one year [10]. This indicates that the maximum solar radiation falling on the horizontal PV systems is around 8.5 kWh/m²/d in December and January (summer seasons), while the lowest value is around 2.7 kWh/m²/d in June and July (winter seasons). Therefore, in December and January, rooftop solar PV systems in the SWIS have a larger energy yield for PV systems, which will easily cause reverse power flow on power grids during daytime hours because of the larger exceeded solar PV generation.
Figure 2.1. Daily Solar Radiation—Horizontal Data of WA (Latitude: -31.9°N; Longitude 115.9°E) [10].

2.2 Rooftop PV Installations in the SWIS

In the SWIS network, as of November 2017, the overall installed capacity of rooftop PV systems is about 684 MW [11], which is around 10 times higher than the capacity in 2011 [12]. The most recent year, from 2016 to 2017, had the largest increase in the capacity of rooftop solar PV systems (by around 125 MW) [12]. Around 25.4% of homes have a rooftop PV system [9], which is slightly lower than South Australia (30.5%) and Queensland (31.6%) [12]. Meanwhile, the average installation size of a PV system increased to 5.3 kW, which is almost double the size of 2011 (2.6 kW) [12]. The continuing increase of rooftop solar PV penetration has reduced the household peak load demand in WA. The peak demand during the 2016 to 2017 summer was estimated to reduce by 207 MW [12], which is the largest reduction since 2009 [12].

In WA, rooftop PV systems are predicted to steadily increase in the future, for several reasons. First, the declining price of rooftop PV systems means they are more affordable for customers to install [12]. Second, increasing the cost of electricity is encouraging consumers to install PV systems to achieve self-consumption of PV electricity. Thirdly, consumer behaviours are
believed to be changing [12], with more people realising the benefits of investigating state-of-the-art technologies to optimise their electricity use.

2.3 Summary

Western Australia has a good supply of solar radiation falling on residential rooftops, particularly in December and January. This energy should be used to generate solar electricity to compensate for the limited amount of fossil fuels. The capacity of rooftop PV systems in the SWIS has been estimated to increase continuously, which has the potential to create new challenges to the power grids. Therefore, it is necessary to investigate approaches to deal with the significant issues resulting from high penetration of PV systems.
Chapter 3: Literature Review

Voltage rise in high photovoltaic (PV) penetration distributed networks is a significant issue highlighted by the International Energy Agency’s (IEA’s) Task 14 - High Penetration PV in Electricity Grids, Subtask 2 – High PV Penetration in local distribution grids in [4] and many approaches have been proposed to mitigate voltage rise. This review involves a broad range of methods that have been categorised according to those who have applied them: prosumers, utilities and a combination of both. State-of-the-art voltage-management approaches with local control strategies will be discussed and new approaches that have not yet been widely implemented will also be presented.

3.1 Technical Solutions from Prosumers

IES with PV modules and batteries, as well as the control features of electrical appliances owned by prosumers, have been marketed as having voltage-management abilities in high PV penetration distributed networks, as stated in [14]. Stetz et al. [4] indicate that if electrical appliances are used to mitigate rises in voltage, prosumers will be required to improve self-consumption. However, this review is not concerned with load-management solutions to self-consumption and focuses instead on solutions using IES.

3.1.1 IES with PV modules and Batteries

Although PV and battery-based inverters have different control methods, IES with PV modules and batteries have similar control functions in mitigating rise in voltage [15]. These include active power (P) control and reactive power (Q) control [15]. Figure 3.1 and Equation 1, as adapted from [16], present the ways in which the P and Q functions work. Equation 1 shows

---

3 As explained in [13], this control requires no communication infrastructure in the network and each device can control itself through programmed information.
that an approximated voltage potential across a grid impedance is a function of $P$ and $Q$. To mitigate voltage deviation ($\Delta V$), approaches that either reduce $P$ or absorb $Q$ can be applied. From the active power control perspective, the Electrical Power Research Institute [15] noted that battery-based inverters have an extra energy storage management function as opposed to PV inverters, as batteries can absorb real power. A combination of common IES’s $P$ and $Q$ control functions from [15] and [16], for both PV and battery inverters at low voltage (LV) levels, is summarised in Table 3.1 and each control method will be analysed in the section that follows.

\[
\Delta V \approx \frac{(R*P) + (\mu Q*X)}{(V_{grid})^2}
\]

Equation 1

where:
$\Delta V$ = voltage deviation from the distributed generation to the grid
$R$ = grid resistance
$X$ = grid reactance
$P$ = active power of distributed generator
$Q$ = reactive power of distributed generator
$V_{grid}$ = grid voltage
$V_{PCC}$ = voltage at the point of common coupling

Figure 3.1: Circuit of the Embedded System Connected to the Distributed Grid
3.1.1.1 Reactive power control

In traditional power networks, reactive power control supports voltage stability at high voltage (HV) levels [4]. However, this control is now being used to reduce voltage rise in distributed networks using embedded distributed generation by absorbing reactive power through the following three methods (as mentioned above):

- Fixed power factor ($\cos \varphi$ (fixed))
- Watt-power factor response ($\cos \varphi$ (P))
- Volt-Var response (Q(V))

Figure 3.2, adapted from [17], presents the differences between the first two listed methods: $\cos \varphi$ (fixed) and $\cos \varphi$ (P). The bottom horizontal line shows the first method and the power factor is fixed at 0.9 or 0.95, at which value it can be programmed into inverters to absorb reactive power [4]. The top curve presents $\cos (\varphi)$ as a function of $P$. When PV generation reaches a certain active power (P), inverters will start to absorb reactive power. Figure 3.3 presents the third method, Q(V), which, as suggested in [18], can directly alter reactive power through voltage changes in two ways: with and without a voltage dead-band. The term ‘voltage dead-band’ here means a voltage band for which voltage variation has no influence on reactive
power [18]. In summary, three different reactive power control methods can be used to mitigate voltage rise in different ways.

![Graph depicting the relationship between the power factor and the active power of inverters.](image1)

**Figure 3.2**: Relationship Between the Power Factor and the Active Power of Inverters [17]

![Graph depicting the relationship between the reactive power and the inverter voltage.](image2)

**Figure 3.3**: Relationship Between the Reactive Power and the Inverter Voltage
Studies [13] and [16] have been performed to evaluate and determine the effectiveness of these reactive power control methods. Although Stetz [13] concluded that the three control methods have similar influences on mitigating voltage rise in the case study, Kraiczy et al. [16] indicate that it is difficult to compare different methods because the grid impedance has an influence on their effectiveness. Therefore, a case-by-case analysis is required to ascertain which reactive power control is the most effective.

Although the three reactive power control methods are commonly applied in many countries, as in [16], and summarised in standards—for example, AS/NZS 4777.2; see [19]—their weaknesses also need to be identified. First, Kraiczy et al. [16] highlight the difficulty in determining inverter control parameters even in the same country. For example, Figure 3.3 shows that different distributed system operators (DSOs) often have diverse control requirements for Q(V) controllers [16]. Second, high PV penetration with reactive power control will eventually cause grids to undergo rising reactive power demand, as stipulated in [20]. This will inadvertently cause unexpected energy losses and will require an additional reactive power supply; for example, through capacitors or a static synchronous compensator (STATCOM) [16]. Third, the three reactive power controls are dependent on solar PV generation, hence their controlled inverters will be idle at night. Research in [21] suggested a full-time Q(V) mode, which would enable IES to work at night and to provide reactive power control. This would keep the voltage within the permissible range at night [21]. A case study in [22] indicated that fulltime Q(V) control improves the voltage at the end of the feeder in the worst case scenario at night (under maximum load and with no solar energy) and revealed that this control is the most advanced control option when compared with the three reactive power control strategies mentioned above.

3.1.1.2 Active power control
3.1.1.2.1 Power curtailment and volt–watt response (P(V))

Power curtailment [23] and volt–watt response P(V) control, as discussed in [16], are two approaches used by inverters to reduce the active power of PV systems. Figure 3.4, adapted from [23], shows that power curtailment control is based on a set voltage point for reference. When the voltage is higher than the reference level, inverters start to curtail surplus energy by operating the PV array away from the maximum power point (MPPT) towards the open circuit voltage, as shown in [23]. Alternatively, Figure 3.5, taken from [17], shows that the P(V) response is a voltage-dependent active power control, which allows more flexibility in terms of controlling the power output from the PV generation. However, although these two methods can alleviate rises in voltage, they restrict the increase of PV penetration.

Figure 3.2: Power Curtailment Method
3.1.1.2.2 Battery storage

Batteries can store chemical energy and release electrical energy to supply prosumers during the night [24]. Different chemical types that are used for battery storage are outlined in [25]. However, of the technologies mentioned in [25], Lithium ion performs better than the others in terms of specific key parameters, such as lifetime, efficiency, depth of discharge (DOD) and hazards. To mitigate voltage rise at LV levels, two types of batteries are categorised in [4] according to their placements. Grid-scale batteries [14] are installed on medium voltage (MV) or LV networks. ‘Behind-the-meter’ batteries are commonly located in households [14]. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) [14] indicated that ‘behind-the-meter’ battery storage systems perform better than grid-scale batteries when managing distributed voltages, since they are close to the distributed generation and avoid energy losses over the network.

‘Behind-the-meter’ battery storage systems with PV inverters can be categorised as either ‘AC coupled’ or ‘DC coupled’ systems [24]. Figure 3.6, adapted from [26], shows that ‘AC coupled’ refers to two IES with battery storage and PV sources separately connected to the AC terminal [24], while the ‘DC coupled’ system in Figure 3.7, from [26], incorporates PV and batteries that are connected to the DC side of one inverter [24]. To easily retrofit existing rooftop PV
systems with added battery systems, the ‘AC coupled’ system is preferred [24]. Moreover, from a technical perspective, Sulaeman et al. [27] noted that ‘AC coupled’ performs better than ‘DC coupled’ in the maximisation of self-consumption and the reduction of system losses. In addition, by coordinating battery storage with the reactive power control of inverters, an additional ‘AC coupled’ inverter will lead to better reactive power control to manage voltage [4].

![Diagram of AC Coupled System](image1)

**Figure 3.4: AC Coupled System [26]**

![Diagram of DC Coupled System](image2)

**Figure 3.5: DC Coupled System [26]**

Apart from the above-mentioned factors for mitigating rise in voltage, research in [28], [29] and [30] highlighted the significance of managing battery control strategies, because this determines how much PV energy can be absorbed during the charging period to prevent reverse power flow. The authors of [28], [29] and [30] discussed how the charging rate of batteries

---

4 The rate of charge in amperes varies with the capacity of the battery [31].
needs to be carefully selected. Zeraati et al. [28] explained that if the charging rate is too rapid, the battery will charge too quickly and the rise in voltage will once again appear when the battery is fully charged. However, if the charging rate is too slow, the peak load cannot be effectively reduced. Alam et al. [29] and Deeba et al. [30] revealed that the charging rate varies as the day progresses. Figure 3.7 a) shows that the PV profile rises to the highest value at midday and gradually decrease to zero; in this figure, the bottom curve represents the load profile. Therefore, the recommended charging strategy in [29] and [30] indicates that the battery charging regime should align with the PV power profile during the period T when the PV generation is higher than the load profile, as shown in Figure 3.8 b).

Figure 3.6: a) PV Output and Load Profile During PV Working Period; b) Battery Charging Regime [29][30]

Although the battery storage systems are beneficial for alleviating rises in voltage, they have significant drawbacks that will limit their development. In 2016, a field trial [14], was undertaken to evaluate the performance of a distributed battery storage system in a high PV
penetration area in Newington, Australia. The trial found that the batteries delivered poor performance at high temperatures or after prolonged usage (for over five months) [14]. Thus, battery technologies need to be improved to work at high temperatures with longer durability. In addition, the battery owners’ main reason for installing ‘behind-the-meter’ storage systems is to store solar energy for later use in supplying night loads, as discussed in [25], rather than mitigate voltage rise in distributed networks. Hence, utilities and prosumers may have conflicting interests.

3.2 Technical Solutions From Utilities

The main device provided by utilities to regulate voltage in distributed networks is the MV/LV transformer, in [14], which can regulate voltage by changing the transformer ratio. Further, to better compensate for over-voltages, reactive compensation devices can also be considered for networks [32]. This section will describe state-of-the-art and advanced MV/LV transformers and a typical reactive power control device.

3.2.1 On-load Voltage Regulating Distribution Transformers (OL-VRDTs)

OL-VRDTs refer to those distribution transformers with on-load tap chargers, which have the ability to regulate voltage when they are connected to loads, as described in [33]. Rauma et al. [34] identified that utilities are becoming more interested in OL-VRDTs, because they can effectively decouple voltages in LV networks with high rooftop PV penetration. This type of MV/LV transformer is becoming popular in Germany [35].

The research in [33] outlined three elements of OL-VRDTs: the control element, the transformer and the control unit. The on-load tap changer is the control element attached to the transformer [33]. Weedy [36] classified the on-load tap changer (OLTC) into two groups—the resistor type and the reactor-type—that avoid interrupting the load current during the tap
changing period [36]. Figures A.1, A.2 and B.1 in Appendices A and B show how these two types of OLTC switch taps, as evident in [36] and [37]. To maintain secondary voltage regulation within the permissible range, it is necessary to implement control strategies through the control unit of the OL-VRDT.

The common autonomous local control strategy accomplished by the control unit has been discussed in [13]. Figure 3.9 shows four necessarily specific control parameters noted by [13] that need to be initially fixed: the OLTC dead-band’s upper and lower limit (V<sub>DB+</sub>, V<sub>DB-</sub>), the nominal set-point voltage at the secondary side of the transformer (V<sub>n</sub>) and the delay time (t<sub>2</sub>-t<sub>1</sub>). The research in [33] recommended that the OLTC dead-band gap be 1.6 times the step voltage. For example, if the step voltage is 1%, the dead-band width should be 1.6%. The delay time regulates how long it takes for the over-voltage to start being reduced to the required specific limits by performing the tap change at t<sub>2</sub> [33]. Figure 3.9 shows that when the voltage curves away from the dead-band, it will return after a delay (t<sub>2</sub>-t<sub>1</sub>). The research in [13] indicates that the lower the value for V<sub>n</sub>, the higher the PV penetration in the distributed networks before the voltage rise.

![Figure 3.7: Autonomous Local Control Strategy of OLTC](image)

A Belgian field trial in [38] evaluated the performance of different OLTC control algorithms, including the local autonomous control (mentioned above), a remote control with
communication infrastructure and a line drop compensation (LDC) control. The LDC control strategy was considered the preferred control method for mitigating voltage rise in Belgium in the future [38]. This is because it was able to manage the overall voltage of the networks, rather than focusing only on the LV networks, which is all that the autonomous local control can do. Further, as discussed in [38], the LDC is not required to investigate communication devices as a remote control strategy.

The theory behind the line drop compensation–voltage rise compensation (LDC–VRC) technique in [37] is that the voltage at the remote site is kept constant by varying the set-point voltage (Vs) of the secondary side of the transformer through power flow (see Figure 3.10). This is an extension strategy based on conventional LDC control [37], which not only compensates for the voltage drop along the feeder with conventional purpose, but mitigates voltage rise and regulates the voltage at the end of the feeder within limits. Equation 2, adapted from [37], reveals that the compensated-for voltage depends on the transmission line’s impedance: \( R + jX \) (see Figure 3.10). Therefore, for LDC–VRC control, it is important to determine the feeder impedance.

\[
V_m = V_s - \Delta V = V_s - I(R + jX)
\]

Equation 2

Where:

\[
\Delta V
\]

Figure 3.8: Example Single Line Diagram for LDC–VRC OLTC Control
Vm = remote site measured voltage
Vs = sending-end voltage
ΔV = voltage drop over feeders
I = load current

From the above discussion, if the two elements in OL-VRDTs—the control element and the control unit—select appropriate values for the impedance compensation of the LDC–VRC function and the four parameters of OLTC control, the LDC–VRC control with OLTC will perform best when managing voltages for distributed networks. Lastly, although different transformers have different taps, the transformer exhibits no noticeable differences when mitigating voltage rise [34]. The study in [34] indicated that a transformer with five positions (1.75% per step voltage) resulted in 69% PV penetration in distribution networks, while the other transformer with nine positions (1.75% per step voltage) resulted in 71%.

The most advanced OL-VRDT-related manufacturers and products to date are listed in Table 3.2. These two transformers require an additional automatic voltage regulator to manage distributed voltages, as seen in [39] and [40]. Wilson Power Solutions [40] selected the automatic voltage regulator from Maschinenfabrik Reinhausen (MR), a leader in OLTC technologies [40]. The latest product from MR is the ECOTAP VPD OLTC and automatic voltage regulator, as shown in [41] and [42]. In a personal interview with Dr Thomas Smolka from MR, he noted that the ECOTAP VPD is compatible with any brand of transformer. Moreover, Dr Smolka indicated that the LDC function in the automatic voltage regulator of the ECOTAP VPD can monitor bi-directional power flow [42].

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Product Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABB</td>
<td>Smart-R-Trafo transformer [39]</td>
</tr>
<tr>
<td>Wilson Transformer</td>
<td>Wilson e2+ Amorphous [40]</td>
</tr>
</tbody>
</table>

Table 3.2: Products for Distributed Transformers
3.2.2 Static Synchronous Compensator (STATCOM)

Research in [32] showed that a STATCOM is a shunt connected controller that is regarded as a typical reactive compensation device because of its small size, low harmonic\(^5\) production and capability for balancing three-phase voltages. Figure 3.10, as adapted from [44], shows that a STATCOM comprises a transformer, inverters and a capacitor.

![Connection Sketch of a STATCOM Device](image)

Figure 3.9: Connection Sketch of a STATCOM Device

Although research in [4] and [32] illustrated that reactive compensation devices mitigate voltage rise by using reactive power control, the utilisation of a STATCOM is costly and requires complex electronic power devices [45].

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\(^5\) The ‘sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency’; see [43].
3.3 Technical Solutions From Both Utilities and ‘Prosumers’

To keep voltage within reasonable limits in distributed LV networks, the active and reactive power control of IES with batteries and PV inverters can be coordinated with the voltage regulation devices included in utility distribution transformers, such as OLTC and LDC.

Considering the reactive power control of IES, Stetz [13] evaluated the performance of a coordinated method, using OLTC-distribution transformers and the reactive power control of PV IES, by comparing it with the sole OLTC-based strategy. However, Stetz found that this combination is rarely useful for mitigating voltage rise [13]. The results in [13] show that the combination of OLTC and PV inverter-based control only improves the voltage performance on certain grids, whereas a solely OLTC-based strategy cannot achieve voltage control. This means that the reactive power control of IES dominates the voltage control in this case, as opposed to the combined strategy. However, some equipment suffered from overloading as a consequence of additional reactive power flow from the IES, which did not occur in the single OLTC-based method [13]. Research in [14] revealed that the Q(V) or cosφ (fixed) control for the PV IES can be coordinated with LDC in HV/MV transformers to mitigate voltage rise. The results of [14] show that even though cosφ (fixed) control produces a better performance in terms of reducing voltage rise, the Q(V) control results in a lower reactive power demand.

Conversely, in terms of the active power control of IES, coordination of ‘behind-the-meter’ battery storage systems and OLTC-distributed transformers is introduced in [46]. Liu et al. [46] discussed how batteries store surplus active power from PV generation, which relieves the working stress of the existing OLTC-distribution transformers. However, this method is dependent on an additional coordinated remote controller [46], which is beyond the scope of this literature review.
Chapter 4: Methodology

Based on the advanced voltage rise mitigation methods summarised in the literature review (Chapter 3), this chapter critically analyses these methods’ feasibility and selects appropriate approaches for this study from the three categories of prosumers, utilities and the combination of both.

The chosen approaches will be required to perform their voltage regulation function by pre-programming their input information, without using communication devices. This parameter programming will use the DIgSILENT PowerFactory 2017 software package. This software has proven benefits for analysing interactions between power grids [47], as well as for providing sufficient advanced elements of distributed generation source and state-of-the-art power electronics [47]. In addition, this software helps evaluate the final selected methods by providing load flow calculations, which contributes data on voltage for every bus, power flow and grid loss [47].

The final chosen approaches are presented in the shaded area in Table 4.1. These approaches were chosen for the following reasons. First, comparing the reactive power control with the active power control of IES from prosumers’ perspective, the active power control using ‘behind-the-meter’ battery storage systems was found to be a better solution. This is because battery storage systems can not only shift the exceeded PV power output to reduce the night time peak load, but can also eliminate energy losses and reactive power demand from the reactive power controls of IES. However, IES with battery storage systems involve battery control strategies to accomplish the charging and discharging procedure. This control is beyond the fundamental function of the battery element in the PowerFactory, which only focuses on the value of active power. Therefore, IES with battery storage systems will not be examined in
this study. IES with reactive power controllers will be coordinated with the methods from utilities to manage LV voltages.

Second, considering the equipment supplied by utilities, this project mainly examined on-load voltage regulation distribution transformers (OL-VRDTs) with and without line drop compensation (LDC). As introduced in Chapter 3, the OL-VRDTs have benefits in reducing the voltages of distribution networks, yet have not been commonly used by utilities. Therefore, it is valuable to evaluate their voltage rise mitigation capability with the representative feeder of WP. Moreover, an additional cooperation with LDC was analysed because of a lack of experience of implementing LDC in distribution transformers. The Static Synchronous Compensator (STATCOM) was the second suggested utility equipment in Chapter 2; however, this was not studied in this project because of its high capital investment.

Third, since Chapter 3 indicated that the characteristics of grids have a significant influence on determining whether the combination methods between the reactive power control of IES and OL-VRDTs can mitigate more voltage, this study examined the coordinated methods in the representative WP network. To simplify the process, only the Q(V) and cos (fixed) of the three reactive power controls of IES were examined, given that cos (P) has a similar function to cos (fixed), as described in Chapter 3. In addition, OL-VRDTs with and without LDC can be combined with the advanced Q(V) fulltime control, which can manage voltage at night and avoid voltage variations.

In conclusion, this study mainly focused on the voltage control of OL-VRDTs with and without LDC. To maximise their voltage rise mitigation capability, this study examined the combination methods with the support from prosumers’ reactive power controllers.
<table>
<thead>
<tr>
<th>Utilities</th>
<th>Prosumers</th>
<th>$\cos \phi = 1$ (Inverter at unity power factor)</th>
<th>Reactive power control of IES</th>
<th>Active power control of IES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\cos \phi = -0.95$ (absorbing vars)</td>
<td>$\cos \phi$ (P)</td>
</tr>
<tr>
<td>Fixed-tap distribution transformers (FT-DTs)</td>
<td>Original network</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OL-VRDTs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OL-VRDTs with LDC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STATCOM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 5: Comparative Analysis of the Previously Studied Network

Given that this project is an extension study of a previous thesis [7], this chapter compares the voltage management of the core methods in this project—OL-VRDTs (with and without LDC)—with that of the fixed tap distribution transformers (FT-DTs) used in the previously studied distribution network (Figure 5.1). This chapter aims to evaluate the influence of the grid characteristics on the voltage rise mitigation capability of the selected strategies before they are implemented in the new distribution network in Chapter 6.

Figure 5.1 indicates the previous power network built by Lu [7], with two 132/22 kV transformers with on-load tap changers (OLTCs) and six 22 kV/415 V FT-DTs. Table 5.1 lists the detailed parameters for these two types of transformers. In addition, the maximum load of each cluster (20 houses per cluster) in the distribution networks is assumed to be 0.08 MVA (4 kW per house), and the minimum load was set at 0.04 MVA (2 kW per house).
Figure 5.1. Example Feeder (Red Line) with LV Distribution Network Modelled by the PowerFactory [7].
Table 5.1: Input Information for Two Types of Transformers in the Original Network (Shown in Figure 1)

<table>
<thead>
<tr>
<th>Type</th>
<th>132 kV/22 kV transformer with OLTCs</th>
<th>22 kV/415 V transformer with fixed-tap changers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>Wye–wye connection 20 MVA</td>
<td>Delta–wye connection 0.63 MVA</td>
</tr>
<tr>
<td>Positive sequence impedance</td>
<td>0.02 + j0.1 pu</td>
<td>0.01 + j0.06</td>
</tr>
<tr>
<td>Tap position</td>
<td>Variable</td>
<td>4</td>
</tr>
<tr>
<td>Additional voltage per tap</td>
<td>1.4%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Voltage setpoint</td>
<td>1.02 pu</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Neutral position</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>Min position</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Max position</td>
<td>21</td>
<td>5</td>
</tr>
<tr>
<td>Controller time constant</td>
<td>60 s</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>

This comparison was based on the maximum allowable amount of rooftop solar PV generation that can be operated before voltages exceed acceptable limits, as determined by implementing different methods.

In the previous study [7], the acceptable voltage limit in the distribution network was between 0.96 and 1.04 pu. This was regulated based on the technical guidelines of WP [48]. For LV networks that are lower than 6 kV, the steady-state voltage range in the normal condition is ±6% (0.94 to 1.06 pu) [48]. However, LV cables connected to each house’s switchboard lead to a ±1% voltage variation. The OLTC attached to the substation transformer introduces a further ±1% uncertainty in the actual voltage because of the OLTC deadband. Therefore, in the previous study, the voltage in the distributed networks was regulated within ±4%.

5.1 Voltage Management Using FT-DTs

In the previous study [7], two scenarios were conducted with the implementation of the original FT-DTs. One scenario operated under the maximum load, without any rooftop solar PV systems, as shown in Figure 5.2. This provided the maximum voltage drop and the lowest voltage at the
remote cluster of the example feeder (red line in Figure 5.1) in this network (0.948 pu). Although the fixed-tap changer was set with a 2.5% voltage boost (at tap position 4), it had a poor voltage regulation ability and could not increase the voltage at the LV side of the distribution transformer (Bus 29) to 1.025 pu, as shown in Figure 5.2. The second scenario operated under the minimum load, with an increasing level of solar PV generation, as shown in Figure 5.3. This scenario aimed to determine the maximum allowable solar PV generation that was regulated under the upper voltage limits. Figure 5.3 indicates that the maximum solar PV generation for each house was around 2.3 kW, which caused the voltage at the remote cluster to be approximately equal to the voltage upper limit.

Figure 5.2. Voltage Profile for Buses Along Example Feeder in Base Case Scenario (Maximum Load without Solar Generation) with Fixed-Tap Changer at Position 4 aiming to Gain Desired Voltage of 1.025 pu at Bus 29.
5.2 Voltage Management Using the OL-VRDTs with and without LDC

Before replacing the original FT-DTs with the OL-VRDTs (with and without LDC), it was necessary to understand how to program these two new devices through the PowerFactory to control voltages. First, for the OL-VRDTs, Table 5.2 displays the input information for the OLTC. The first five parameters were fixed thoroughly in this study. There are two choices for the operation mode of tap changers: continuous and discrete. The continuous tap changer was assumed to apply in this study because it is typically used for modelling purposes, and helps tap controllers adhere to the desired setpoint voltage through a large number of tap steps [47]. However, discrete control allows uncertainty to exist when controlling voltages with integer tap changes. Moreover, the tap changers are operated at the LV side of the distribution transformers to control the voltage in the LV networks. During an interview, Dr. Smolka suggested that a 10-second delay is required to avoid the overrunning of the tap changer because of large voltage fluctuations over short time period. The only uncertainty is the setpoint voltage \( V_{set} \), which
fundamentally determines the voltage management capability of OL-VRDTs and needs to be set based on different cases.

Table 5.2: Input Information for OLTC in the DlgSILENT PowerFactory

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap changer</td>
<td>Continuous</td>
</tr>
<tr>
<td>Position of controlled node</td>
<td>LV</td>
</tr>
<tr>
<td>Control mode</td>
<td>Voltage control</td>
</tr>
<tr>
<td>Setpoint</td>
<td>Local</td>
</tr>
<tr>
<td>Time delay</td>
<td>10 s</td>
</tr>
<tr>
<td>Voltage setpoint ($V_{set}$)</td>
<td>Need to be determined</td>
</tr>
</tbody>
</table>

Second, the voltage management of OL-VRDTs with LDC control requires three additional parameters (Table 5.3) alongside the information outlined in Table 5.2. The first two parameters are assumed for the connected current and voltage transformers inside the LDC controller. LDC impedance needs to be adjusted with the $V_{set}$ of OL-VRDTs to control voltages.

Table 5.3: Input Information for LDC in the DlgSILENT PowerFactory

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current transformer rating</td>
<td>500 A</td>
</tr>
<tr>
<td>Voltage transformer ratio</td>
<td>100</td>
</tr>
<tr>
<td>$R_{set}, X_{set}$</td>
<td>LDC impedance</td>
</tr>
</tbody>
</table>

Comparing OL-VRDTs (with and without LDC) with FT-DTs required the voltage regulation range of FT-DTs to be fixed. This meant that the studied nine tap positions the OL-VRDTs needed a total 10% voltage regulation range, as with the FT-DTs (Table 5.1). Thus, the additional voltage per step for OL-VRDTs was 1.25%, as shown in Table 5.4. In addition, it was necessary to fix the voltage profile for the example feeder generated under the maximum load without solar PV generation, with the use of FT-DTs, because this voltage profile could be used to determine the variables for the OL-VRDTs and LDC (Table 5.4). This could be
achieved by continually testing and adjusting the variables so that, at the remote cluster under the condition of maximum load with no solar generation, the voltage would remain at the same value as the lowest voltage attained in the FT-DTs case (0.948 pu; see Figure 5.2). The following section explains how these variables were detected, and compares the voltage profiles before and after changing the FT-DTs under the high solar generation scenario to effectively analyse the voltage regulation abilities of the different strategies.

Table 5.4: Input Information for the 22 kV/415 V OL-VRDTs with and without LDC

<table>
<thead>
<tr>
<th></th>
<th>22 kV/415 V OL-VRDT without LDC</th>
<th>22 kV/415 V OL-VRDT with LDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Delta–wye connection</td>
<td>Delta–wye connection</td>
</tr>
<tr>
<td>Rated power</td>
<td>0.63 MVA</td>
<td>0.63 MVA</td>
</tr>
<tr>
<td>Positive sequence impedance</td>
<td>0.01 + j0.06</td>
<td>0.01 + j0.06</td>
</tr>
<tr>
<td>Tap position</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Additional voltage per tap</td>
<td>1.25%</td>
<td>1.25%</td>
</tr>
<tr>
<td>Voltage setpoint</td>
<td>Variable</td>
<td>Variable</td>
</tr>
<tr>
<td>Neutral position</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Min position</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Max position</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Tap changer operation mode</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td>Controller time constant</td>
<td>10 s</td>
<td>10 s</td>
</tr>
<tr>
<td>Current transformer rating</td>
<td>Not available</td>
<td>500 A</td>
</tr>
<tr>
<td>Voltage transformer ratio</td>
<td>Not available</td>
<td>100</td>
</tr>
<tr>
<td>$R_{set}$</td>
<td>Not available</td>
<td>Variable</td>
</tr>
<tr>
<td>$X_{set}$</td>
<td>Not available</td>
<td>Variable</td>
</tr>
</tbody>
</table>

5.2.1 OL-VRDTs

$V_{set}$ was the only variable of OL-VRDTs (Table 5.4) that could be adjusted to 1.002 pu to cause the voltage at the end of the feeder to be 0.948 pu. This adjustment caused the voltage profile in the base case scenario to be almost the same as that of the FT-DTs (Figure 5.4). The orange curve of Figure 5.4 shows the voltage profile determined using the OL-VRDTs. This controller maintained a constant voltage at the LV side of the distributed transformer (Bus 29) at 1.002 pu.
pu. This effectively reduced the voltage rise along the LV feeder. Compared with the FT-DTs (upper part of Figure 5.5), the OL-VRDTs showed a consistent voltage drop or rise along the LV feeder (∆V) under the same solar PV generation, keeping the same Bus 29 voltage difference between the OL-VRDTs and FT-DTs cases. However, with the increased solar PV generation, Figure 5.5 shows that the difference in Bus 29 voltage between the two cases increased (∆V'), and a larger voltage rise was mitigated by OL-VRDTs. The OL-VRDT (with a setpoint voltage at 1.002 pu) caused the maximum permissible solar PV generation on the LV feeder to be 4.5 kW/house, which did not cause the voltage at the end of the feeder to exceed the upper voltage limit, as shown in Figure 5.5.

![Figure 5.4. Voltage Profiles for Buses on Feeder in FT-DTs (upper blue curve) and OL-VRDTs without LDC (lower orange curve) under the Maximum Load, without Solar PV Generation.](image-url)
5.2.2 OL-VRDTs with LDC

As shown in Figure 5.6, the list of options for the $V_{set}$, $X_{set}$ and $R_{set}$ caused the voltage profile under the condition of maximum load with no solar to be the same as that of FT-DTs (Figure 5.2). These options were derived by keeping the X/R ratio of the LV cable at 0.2059, and keeping the voltage of the remote cluster at 0.948 pu during the variable adjusting process. This examination began with $R_{set} = 0.01V$, and then $R_{set}$ grew at a step of 0.01 V until the $V_{set}$ dropped to the closet value to the lower limit (0.96 pu). Afterwards, it was necessary to select the better option by analysing their influence on mitigating the voltage rise in high PV penetration.
Figure 5.6. Voltage Profiles for Buses along the Feeder under Seven Different Options for the Variables of $V_{set}$, $X_{set}$ and $R_{set}$.

Figure 5.7 shows that, when there were no rooftop solar PV systems, the lowest voltages in Cluster 3 determined by Options 6 and 7 were lower than the voltage lower limit. Hence, these two options were not considered. The other five options had different voltage rise mitigation
capabilities by observing the maximum allowable solar PV generation, as shown in Figures 5.8 to 5.12. The maximum allowable solar PV generation (7.5 kW per house) was determined by Option 3 (Figure 5.10), where $V_{set} = 0.986 \text{ pu}$, $R_{set} = 0.03 \Omega$ and $X_{set} = 0.006177 \Omega$.

To further optimise the three variables of OL-VRDTs with LDC control, when each house retained a 7.5 kW solar PV system (determined by Option 3), the analysis still required the three potential variables to have the same voltage profile under the maximum load and without solar PV generation, by keeping the voltage at the end of the feeder (Cluster 3) at 0.948 pu. The following explains how the variables’ option range was determined. Figures 5.9 and 5.11 show that the highest permitted solar PV generation using Option 2 was 6.5 kW/house and using Option 4 was 5 kW/house. Hence, a range of possible variable options—between Options 3 and 2 or between Options 3 and 4—could be examined to keep the maximum solar PV generation in each cluster at 7.5 kW. To detect the variable range, the values for the voltage setpoint were changed at 10 steps between Options 2 and 3 and Options 3 and 4, as shown in Table 5.5. The central shaded area in Table 5.5 shows the available variable options that could satisfy the three requirements, including the $X/R$ ratio (0.2059), the remote cluster voltage at maximum load without solar condition (0.948 pu) and the 7.5 kW solar PV generation.
Figure 5.8. Voltage Profiles for the Buses along the Feeder with the Increase of Solar PV Generation under the Option 1 Condition, with the Minimum Household Load, when $V_{set} = 0.997$ pu, $R_{set} = 0.01 \, \Omega$ and $X_{set} = 0.002059 \, \Omega$.

Figure 5.9. Voltage Profiles for the Buses along the Feeder with the Increase of Solar PV Generation under the Option 2 Condition, with the Minimum Household Load, when $V_{set} = 0.991$ pu, $R_{set} = 0.02 \, \Omega$ and $X_{set} = 0.004118 \, \Omega$. 
Figure 5.10. Voltage Profiles for the Buses along the Feeder with the Increase of Solar PV Generation under the Option 3 Condition, with the Minimum Household Load, when $V_{set} = 0.986$ pu, $R_{set} = 0.03 \, \Omega$ and $X_{set} = 0.006177 \, \Omega$.

Figure 5.11. Voltage Profiles for the Buses along the Feeder with the Increase of Solar PV Generation under the Option 4 Condition, with the Minimum Household Load, when $V_{set} = 0.98$ pu, $R_{set} = 0.04 \, \Omega$ and $X_{set} = 0.008236 \, \Omega$. 
Figure 5.12: Voltage Profiles for the Buses along the Feeder with the Increase of Solar PV Generation under the Option 5 Condition, with the Minimum Household Load, when $V_{set} = 0.975\text{ p.u.}$, $R_{set} = 0.05 \Omega$ and $X_{set} = 0.010295 \Omega$.

Table 5.5: Method for Determining the Variables’ Option Range (Central Highlighted Area) by Keeping the $X/R$ Ratio, Voltage at the End of the Feeder (Cluster 3) of the Base Case Scenario and 7.5 kW Solar PV Generation of Each House
To distinguish between these selected variables, the voltage profiles in distribution networks for each option were generated, as shown in Figure 5.13. This figure indicates that, under the same solar PV generation (7.5 kW), the decrease of $V_{set}$ and increase of $X_{set}$ and $R_{set}$ improved the voltage rise mitigation capability of the OL-VRDTs with LDC controller in the distributed networks.

![Figure 5.13. Voltage Profiles for the Buses along the LV Feeder in Distribution Networks, with the Minimum Household Load, under Four Different Variable Selections.](image)

However, the above outcome seems contradictory to the results from Options 4 and 5 (Figures 5.11 and 5.12), which had larger values for $X_{set}$ and $R_{set}$ and lower values for $V_{set}$. This result was because the selected small $V_{set}$ (0.98 pu) in Option 4 could easily cause the voltage on the LV side of transformers (Bus 29) to be outside the lowest boundary when the solar PV generation increased. Thus, to effectively increase the hosting capacity of the PV systems, the voltage setpoint needed to be carefully chosen and could not be lower than 0.9854 pu in this
case. This meant that the best option for the three variables was when $V_{set} = 0.9854 \text{ pu}$, $R_{set} = 0.031 \text{ V}$ and $X_{set} = 0.006383 \text{ V}$.

Figure 5.14 shows the voltage profile generated when the OL-VRDTs with LDC was implemented using the aforementioned optimised $V_{set}$, $R_{set}$ and $X_{set}$ ($V_{set} = 0.9854 \text{ pu}$, $R_{set} = 0.031 \text{ V}$ and $X_{set} = 0.006383 \text{ V}$). As mentioned in Chapter 2, OL-VRDTs with LDC could keep constant the nominated remote site (load centre) voltage. However, in this study, solar PV generators and household loads were located along the LV feeder, which caused the LV voltage to rise or fall non-linearly. Thus, the load centre point was not kept at a fixed location. Figure 5.14 shows that the rough remote site was just beyond the 20 House Cluster 1.

Figure 5.14. Voltage Profiles for Buses along the Feeder with Different Levels of Solar PV Generation, under the Minimum Household Load Condition, when $V_{set} = 0.9854$, $R_{set} = 0.031 \text{ V}$ and $X_{set} = 0.006383 \text{ V}$.

Comparing the voltage profile in Figure 5.14 with that of OL-VRDTs and FT-DTs (Figure 5.5) indicated that the implementation of LDC allowed a greater range in capacities of rooftop solar PV systems. The most obvious difference from this comparison was that, with the increase of solar PV penetration, using OL-VRDTs with LDC reduced the LV voltage of the MV/LV
transformer. This resulted from the function of LDC, which compensated the voltage drop or rise along the feeder by adjusting the tap positions of the OLTC. Moreover, the OL-VRDTs with LDC had the best voltage rise mitigation capability with the shallowest increase rate (as shown in Figure 5.15), which could host more rooftop solar PV systems of different sizes.

Figure 5.15. Cluster 3 Voltage Profiles for Different Solar PV Generation, under the Minimum Household Load Condition, with the Use of Three Different Distribution Transformers.

Overall, the main reason that the OL-VRDTs (with and without LDC) had better voltage management in the LV network derived from the advanced controlling of the voltage at the LV side of the transformers. Therefore, to finalise the comparison study, it was significant to analyse the influence of the OL-VRDTs on hosting the maximum load, compared with the scenario using the FT-DTs at the maximum load, with no solar generation influence. This comparison not only had to maintain the voltage boost of transformers at 2.5%, but also had to fix the voltage at the remote cluster at 0.948 pu. This requires that the setpoint voltages of the OL-VRDTs need to be fixed at 1.025p.u. It should be noted that there was no need to examine the effect of OL-VRDTs with LDC on the maximum load holding because the distribution
transformer would be on the tap position with the greatest voltage boost, regardless of whether LDC was used or not.

Figure 5.16 shows that the maximum household load for each cluster could be increased from 0.08 MVA (FT-DTs) to 0.113 MVA (OL-VRDTs) before the voltage at the end of the LV feeder dropped to 0.948 pu. This result indicated that, when hosting a larger household load, the OL-VRDTs presented a benefit over the FT-DTs, when these two transformers were set with the same voltage boost. Analysing the maximum permissible load is important for grid planning in the future because there will likely be increasing household load in the future as a result of electrical vehicle charging.

![Figure 5.16. Voltage Profiles for Buses along the Feeder, under the Maximum Loads for Each Case, Using FT-DTs and OL-VRDTs.](image)

**5.3 Summary**

Table 5.6 summarises the maximum permitted solar generation for each house with the implementation of different methods from utilities. FT-DTs are commonly used in networks, yet have the worst voltage regulation ability among the three methods. The OL-VRDTs with and without LDC not only have a better voltage rise mitigation capability, but also have a better
load hosting capability than do the FT-DTs. As a result, the maximum load can be improved by 41.25%, as shown in Table 5.6.

Table 5.6: Summary Table for the Determined Maximum Solar PV Generation and Load Information

<table>
<thead>
<tr>
<th>Devices from utilities</th>
<th>Solar and load information</th>
<th>FT-DTs</th>
<th>OL-VRDTs</th>
<th>OL-VRDTs with LDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar generation kW/house</td>
<td>2.3</td>
<td>4.5</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>Min load kW/house (P&lt;sub&gt;min_load&lt;/sub&gt;)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Ratio of solar generation to the minimum load of each house</td>
<td>1.15 * P&lt;sub&gt;min_load&lt;/sub&gt;</td>
<td>2.25 * P&lt;sub&gt;min_load&lt;/sub&gt;</td>
<td>3.75 * P&lt;sub&gt;min_load&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>Improved maximum load using OL-VRDTs</td>
<td>0</td>
<td>(\frac{(0.113-0.08)}{0.08} \times 100% = 41.25%)</td>
<td>41.25%</td>
<td></td>
</tr>
</tbody>
</table>

In addition, whether OL-VRDTs with LDC control can mitigate greater voltage rise than using a single OL-VRDT depends on the parameters selected for both the OL-VRDTs and LDC controllers. In general, high LDC impedance and a low setpoint voltage of OL-VRDTs promote more voltage rise to be mitigated; however, the setpoint voltage cannot be set extremely low considering the voltage lower limit. Therefore, this control requires continual adjustment to obtain the expected results.
Chapter 6: Representative Network Modelling

This chapter describes the characteristics of a typical MV network in the SWIS and the designated distributed LV network. It presents the general elements of the network as modelled in PowerFactory.

6.1 Distribution MV Network Model

6.1.1 Overview

![Diagram of MV network](image)

Figure 6.1. A Representative 22 kV Feeder in the SWIS Provided by WP.

Figure 6.1 displays a typical 22 kV MV network as part of the SWIS, which was provided by WP. This network consists of several types of cables and loads. The feeder is used to transmit electricity from the alternating current (AC) voltage source to loads. This 22 kV feeder can be categorised into two levels: the main line and branch lines. The main line (see Figure 6.1, orange line) presents the radial transmission line (11.471 km, see Figure 6.2) from the AC voltage source to the end of the feeder, where it has the lowest voltage (0.97761p.u.). The branch lines (Figure 6.1 blue lines) with the loads are connected to the bottom half of the main line.
Furthermore, the end of this 22kV MV feeder is needed to connect to a LV distribution network (415V).

![Diagram showing voltage profile](image)

**Figure 6.2. Voltage Profile for the Representative 22 kV Feeder in Figure 6.1.**

### 6.1.2 MV Network Elements

The representative radial WP 22 kV network includes three types of elements: an AC voltage source, eight levels of loads and 10 types of cables (Figure 6.1), as discussed in the following sections.

#### 6.1.2.1 AC Voltage Source

Figure 6.3 displays the three-phase AC voltage source model used in PowerFactory. In the symmetrical load flow, only a positive sequence is considered. The voltage of this model is determined by the controlled setpoint voltage (voltage input parameter) behind the internal impedance and the voltage difference across the impedance. If the internal impedance can be ignored, the voltage input parameter represents the nominal voltage of this source, which is 21.997 kV (Table 6.1).
Figure 6.3. AC Voltage Source Model Used in PowerFactory.

Table 6.1: Input Information for AC Voltage Source

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line–line nominal voltage</td>
<td>21.997 kV</td>
</tr>
<tr>
<td>Voltage, magnitude</td>
<td>1.01 pu</td>
</tr>
<tr>
<td>Impedance</td>
<td>N/A</td>
</tr>
</tbody>
</table>

6.1.2.2 MV Loads

The loads in the MV network are at their maximum value. Figure 6.4 presents the three-phase load model used in this balanced load flow analysis. This model requires users to choose its input mode type and specify two input parameters to indicate its electrical consumption. In this network, there are eight different levels of loads with specific active power ($P$) and reactive power ($Q$) inputs (Table 6.2).

Figure 6.4. Three-phase Load Model Used in PowerFactory.
Table 6.1: Input Information for the 22 kV Loads with Eight Different Types

<table>
<thead>
<tr>
<th>Load levels</th>
<th>Active power P (MW)</th>
<th>Reactive power Q (Mvar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0054</td>
<td>0.00261534</td>
</tr>
<tr>
<td>2</td>
<td>0.0135</td>
<td>0.006538</td>
</tr>
<tr>
<td>3</td>
<td>0.056</td>
<td>0.042</td>
</tr>
<tr>
<td>4</td>
<td>0.108</td>
<td>0.081</td>
</tr>
<tr>
<td>5</td>
<td>0.1134</td>
<td>0.08505</td>
</tr>
<tr>
<td>6</td>
<td>0.18</td>
<td>0.135</td>
</tr>
<tr>
<td>7</td>
<td>0.2268</td>
<td>0.1701</td>
</tr>
<tr>
<td>8</td>
<td>0.36</td>
<td>0.27</td>
</tr>
</tbody>
</table>

6.1.2.3 MV Cables

The cable system of this network is a grounded parallel single-core copper cable (Figure 6.5). Depending on different electrical parameters, the cables can be categorised into 10 types in two categories (Table 6.3).

![Figure 6.5. MV Cable Model Used in PowerFactory.](image)

Table 6.2: Input Information for the Main and Branch Lines with 10 Different Cable Types

<table>
<thead>
<tr>
<th>Transmission line levels</th>
<th>Name</th>
<th>Rated current (kA) in ground</th>
<th>Resistance ($\Omega/km$)</th>
<th>Reactance ($\Omega/km$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main line</td>
<td>2240_22.0 kV/3</td>
<td>0.475</td>
<td>0.0989</td>
<td>0.103</td>
</tr>
<tr>
<td></td>
<td>3X15_22.0 kV/3</td>
<td>0.463</td>
<td>0.271</td>
<td>0.3207</td>
</tr>
<tr>
<td></td>
<td>3X16_22.0 kV/3</td>
<td>0.471</td>
<td>0.2132</td>
<td>0.3125</td>
</tr>
<tr>
<td></td>
<td>XL52_22.0 kV/3</td>
<td>0.484</td>
<td>0.101</td>
<td>0.111</td>
</tr>
<tr>
<td></td>
<td>XL40_22.0 kV/3</td>
<td>0.31</td>
<td>0.211</td>
<td>0.108</td>
</tr>
<tr>
<td></td>
<td>2203_22.0 kV/3</td>
<td>0.25</td>
<td>0.195</td>
<td>0.0842</td>
</tr>
<tr>
<td>Branch lines</td>
<td>3X12_22.0 kV/3</td>
<td>0.233</td>
<td>0.6793</td>
<td>0.3498</td>
</tr>
<tr>
<td></td>
<td>XL38_22.0 kV/3</td>
<td>0.135</td>
<td>1.11</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>XXXX_22.0 kV/3</td>
<td>0.1</td>
<td>0.4347</td>
<td>0.3355</td>
</tr>
<tr>
<td></td>
<td>2201_22.0 kV/3</td>
<td>0.115</td>
<td>0.757</td>
<td>0.113</td>
</tr>
</tbody>
</table>
6.2 LV Distribution Network Model

6.2.1 Overview

There is a MV load which is $0.1134 \text{ MW} + j 0.8505$ at the end of the MV WP feeder as shown in Figure 6.6. The LV network with distributed solar PV systems is designed to connect to the end of the WP 22 kV feeder. This is because the voltage at the end of the 22 kV radial feeder has the poorest voltage performance under the maximum load condition. Before building a LV network, a substation was built with a 200 kVA 22 kV/415 V transformer to decrease the voltage to 415 V to feed electricity safely to homes.

Figure 6.6 shows that the 22 kV/415 V transformer is connected to two 415 V 95 mm² aluminium feeders. Each LV feeder has three clusters at distances of 25, 125 and 205 metres from the transformer. Every cluster is assumed to be equipped with one PV system and one load. Since the voltage performance along two feeders is the same, this study only recorded the voltage changes on the right side of the 415 V feeders. To supply high-quality electricity to customers in the SWIS, WP recently recommended that the steady-state voltage limit be $+6\%$, $-10\%$ (0.90 to 1.06 pu) [48]. However, the final voltage range in this study was regulated between $+4\%$ and $-8\%$. The reason for this was the 1% voltage variation from the LV cables connecting to each house’s switchboard, as mentioned in Chapter 5. In addition, the AC voltage source on the right top of the 22 kV network is supposed to connect to an outdoor pad-mount MV/LV distribution transformer with an OLTC. The OLTC deadband causes a further $\pm1\%$ uncertainty in the actual voltage. Therefore, the voltage in distributed networks must be regulated between 0.92 and 1.04 pu.
6.2.2 LV Network Elements

6.2.2.1 LV Loads

The MV load at the end of the 22 kV feeder is 0.1134 MW + j0.08505 Mvar. To feed customers with electricity on six clusters, each cluster is assumed to have the maximum LV load—that is, one-sixth of the size of the 22 kV load, at 0.0189 MW + j0.014175 Mvar.

6.2.2.2 Distribution MV/LV Transformer

Figure 6.7 shows that the primary and secondary windings of the 22 kV/415 V fixed-tap transformer are connected in a configuration of delta–star neutral, which is labelled ‘D-Y’ in the software. To prepare for the load flow analysis, careful design for the tap changer is required.
because the tap changer determines the winding ratio of a transformer by selecting the tap position and the additional voltage per step [47]. Table 6.4 presents the specification of the 0.2 MVA transformer. To increase the secondary side voltage of the transformer, the tap was set at Position 2 on the MV side that provides a 2.5% voltage boost. In addition, its impedance was 4%, based on the 0.2 MVA rating.

Figure 6.7. Delta–star Neutral Transformer Model.

Table 6.3: Input Information for the 22 kV/415 V Transformer

<table>
<thead>
<tr>
<th></th>
<th>22 kV/415 V transformer with fixed-tap changers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Delta–wye neutral connection</td>
</tr>
<tr>
<td>Rated power</td>
<td>0.2 MVA</td>
</tr>
<tr>
<td>Positive sequence impedance</td>
<td>0.06 + j0.012</td>
</tr>
<tr>
<td>Tap changer at side</td>
<td>22kV</td>
</tr>
<tr>
<td>Tap position</td>
<td>2</td>
</tr>
<tr>
<td>Additional voltage per tap</td>
<td>2.5%</td>
</tr>
<tr>
<td>Voltage setpoint</td>
<td>Not available</td>
</tr>
<tr>
<td>Neutral position</td>
<td>3</td>
</tr>
<tr>
<td>Min position</td>
<td>1</td>
</tr>
<tr>
<td>Max position</td>
<td>5</td>
</tr>
</tbody>
</table>

6.2.2.3 LV Cables

The underground LV cable type used in the LV network has 95mm$^2$ aluminium phase conductors – the same type as used by Lu [7]. Table 6.5 displays the key impedance parameters for this cable.

---

6 HV side in Figure 6.7 presents the MV side in this study.
Table 6.4: Input Information for the 415 V Cables

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistance (Ω/km)</th>
<th>Reactance (Ω/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>0.372</td>
<td>0.0766</td>
</tr>
</tbody>
</table>
Chapter 7: Load Flow Simulation Results and Discussion

This chapter outlines the voltage profiles and grid losses for the 415 V network under different scenarios of voltage regulation approaches, using load flow analysis. Table 7.1 presents an index of the involved methods. This chapter begins with a base case examination using the original fixed-tap 22 kV/415 V transformer. This examination identifies the maximum voltage drop along the LV feeder under the maximum load ($S_{\text{max\_load}} = 0.0189 \text{ MW} + j0.014175 \text{ Mvar}$) without solar PV generation condition, which must be kept consistent when using other methods. Afterwards, at the minimum load condition, $S_{\text{min\_load}}$ (half of the $S_{\text{max\_load}}$: 0.0945 MW + j0.007087 Mvar), the maximum allowable solar PV generation in each cluster is determined and viewed as an evaluation benchmark. This permitted maximum solar generation is improved by implementing the investigated methods in Table 7.1. To determine the maximum value for solar generation, this analysis gradually increased the PV penetration level. This analysis assumed that the per-step variation of solar PV generation on each cluster was a function of the active power of the minimum load ($P = 0.945 \text{ MW}$); hence, the solar PV generation can be presented as $\frac{n}{2} P$ ($n = 1, 2, 3 \ldots$). The exceeded solar energy that cannot be consumed by customers is $(\frac{n}{2} - 1) P$ (when $n > 2$).

Table 7.1: Voltage Management Approaches for this Study (Shaded Area)

<table>
<thead>
<tr>
<th>Utilities</th>
<th>Prosumers</th>
<th>Reactive power control of IES</th>
<th>Active power control of IES</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT-DT</td>
<td>$\cos \varphi = 1$ (solar inverter at unity power factor)</td>
<td>$\cos \varphi$ (fixed) = -0.95 (absorbing)</td>
<td>$\cos \varphi$ (P)</td>
</tr>
<tr>
<td>OL-VRDT</td>
<td>$\text{Original network}$ 7.1.1</td>
<td>7.1.2.1</td>
<td>7.1.3.1</td>
</tr>
<tr>
<td>OL-VRDT with LDC</td>
<td>7.1.2.2</td>
<td>7.1.3.2</td>
<td>7.1.3.2</td>
</tr>
<tr>
<td>STATCOM</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7.1 Voltage Management with Different Selected Strategies

7.1.1 Base Case Scenario

The upper curve of Figure 7.1 shows the maximum voltage droop along the LV feeder in the base case condition, when the distribution transformer had a +2.5% voltage boost using a FT-DT. This curve indicates that the lowest voltage at the end of the feeder (0.952 pu) had not been reduced to the lower limit at 0.92 pu, which indicates that there is a possibility of increasing LV loads without causing power quality issues. The lower curve in Figure 7.1 shows that the maximum loads in each cluster could be increased to be 1.58 times higher than the assumed maximum load ($S_{max\_load}$). This caused the voltage at the end of the feeder to be reduced to the lower voltage limit (0.92 pu).

![Figure 7.1. Voltage Profile for the 415 V Feeder under the Maximum Load Condition with No Solar (base case) when the Transformer is Designed to Have a 2.5% Voltage Boost.](image)

To examine the ability of the LV feeder to host PV systems, household loads were set at their minimum value, $S_{min\_load}$. Figure 7.2 shows that the maximum allowable solar PV generation in
the LV distribution network was 4.5 P/cluster, which caused the voltage at the end of the feeder (1.039 pu) to be almost the same as the voltage upper limit (1.04 pu). The following investigated methods aim to improve on this result.

Figure 7.2. 415 V Feeder Voltage Profile at the Minimum Load with Increasing Installations of PV Systems.

7.1.2 Technical Solutions from Utilities

The fundamental strategies for selecting appropriate variables for OL-VRDTs with and without LDC are the same as those introduced in the comparative analysis in Chapter 5. Therefore, this section does not present the selection process for variables, especially for the implementation of OL-VRDTs with LDC.

7.1.2.1 OL-VRDT

To create a voltage profile of the LV feeder in this scenario at the current maximum load with no solar generation condition, the same as that in the base case scenario (Figure 7.1), this analysis required the setpoint voltage of OL-VRDTs to be fixed at 0.968 pu, as shown in Figure
7.3, at the controlled bus point. In addition, Figure 7.3 shows that the maximum solar PV generation per cluster before the voltage exceeded the limit was slightly lower than 13 P, which was around three times larger than the result from the implementation of FT-DT, as shown in Figure 7.2.

![Figure 7.3. 415 V Feeder Voltage Profile at the Maximum Load, No Solar and the Minimum Daytime Load, with Increasing Solar PV Generation with the Implementation of the OL-VRDT.](image)

In addition, as mentioned in Chapter 5, it was worth examining how much the current maximum load, $S_{\text{max_load}}$, in the base case scenario using the FT-DT (with 2.5% voltage boost) could be increased by implementing the OL-VRDT with the same voltage boost. To achieve this, the $V_{\text{set}}$ for the OL-VRDT should be programmed at 1.025 pu and kept fixed all the time. However, under the same current maximum load condition, the OL-VRDT in this network increased the voltage at the LV side of DT to 0.995 pu, instead of maintaining the voltage at 1.025 pu. The unexpected voltage at the LV side of the OL-VRDT resulted from the LV in the 22kV network, which was only 0.977 pu. Thus, the voltage was boosted from 0.977 pu to 0.995 pu, as shown by the upper curve in Figure 7.4, which represented a 2.5% voltage boost.
To compare the amount of the maximum LV load capacity derived from the OL-VRDT (set with 2.5% voltage boost) with that determined in the base case scenario, this analysis required the voltage at the remote cluster (0.952 pu) to be maintained, with no changes in the MV loads. The lower curve in Figure 7.5 presents the LV feeder voltage profile with the implementation of OL-VRDT (set with 2.5% voltage boost) under the improved maximum load condition. This updated maximum load was 1.52 times higher than the current maximum load.

Figure 7.4. 415 V Voltage Profiles for OL-VRDT with \( V_{set} = 1.025 \) (Upper Curve) and FT-DT with 2.5% Voltage Boost at the Condition of Current Maximum Load with No Solar Generation.
7.1.2.2 OL-VRDT with LDC

The parameterisation of LDC impedance ($X_{set}$ and $R_{set}$) and setpoint voltage ($V_{set}$) not only had to satisfy the voltage profile under the base case condition, but also had to ensure this combination improved the voltage management ability of solely using OL-VRDTs. The final adjusted variables were $V_{set} = 0.9662$, $X_{set} = 0.007$ and $R_{set} = 0.0014414$, which increased the maximum solar PV generation to be around 14 P per cluster, as shown in Figure 7.6. The load centre was located around the mid-point between the distribution transformer and Cluster 1, as shown in Figure 7.6.
Figure 7.6. 415 V Feeder Voltage Profile at Maximum Load, No Solar and Minimum Daytime Load, with Increasing Solar PV Generation with the Implementation of the OL-VRDT and LDC ($V_{set} = 0.9662$, $X_{set} = 0.007$ and $R_{set} = 0.0014414$).

7.1.3 Technical Solutions from Both Prosumers and Utilities

This section examines the influence of the combination methods on improving the voltage rise mitigation capability of solely implementing an OL-VRDT or OL-VRDT with LDC.

7.1.3.1 OL-VRDTs + Reactive Power Controls of IES

To compare these combination methods with OL-VRDTs for reducing voltage rise, the examination began when the solar generation was 12 P/cluster. This was the maximum allowable solar PV generation when the OL-VRDT was solely applied in the LV network.

7.1.3.1.1 OL-VRDT + Cos $\psi$ (Fixed)

The $\cos \psi$ (fixed) controller relays the selection of the power factor to act as an inductor, which can then absorb reactive power to mitigate voltage rise. This power factor was set at -0.95 for this study. Figure 7.7 shows that this combination strategy mitigated more voltage rise in the LV network than the result from the sole OL-VRDT scenario. The maximum solar PV
generation was 14 P/cluster, which caused the voltage at the remote cluster to be approximately the same as the voltage upper limit. This 2 P increase in solar PV output was contributed by the reactive power absorption by using PV inverters.

Figure 7.7. 415 V Feeder Voltage Profile at the Minimum Daytime Load with Increasing Solar PV Generation with the Implementation of the OL-VRDT and \( \cos \varphi \) (fixed).

7.1.3.1.2 OL-VRDTs + Q(V)

To evaluate the Q(V) control, input information for voltage droop, voltage deadband and ±Q limits needed to be pre-programmed. In this study, voltage management with and without voltage deadband were examined separately. For both of these cases, the voltage limits were 0.95 pu and 1.05 pu, which generated the maximum capacitive vars (Q rated) and inductive vars (-Q rated). These ±Q limits needed to be determined based on the active power output of PV generation and the assumed power factor (±0.9 PF). The dotted curve in Figure 7.8 passed through the setpoint voltage point (1.0 pu) without using the voltage deadband. With voltage increase to higher than 1.0 pu, the Q(V) controller started to increase the reactive power absorbing level, until the maximum value at -Q rated with a voltage droop value at 5% was attained (from 1.0 to 1.05 pu). However, the solid line in Figure 7.8 indicates that the voltage
regulation was limited by a ±1% voltage deadband between 0.99 and 1.01 pu, with a 4% voltage droop, which avoided fulltime voltage control and unexpected reactive power demand.

![Diagram showing Q(V) control function with setpoint voltage and voltage limits regulated by PF = ±0.9)](image)

**Figure 7.8.** Q(V) Control Function (±Q Limits Regulated by PF = ±0.9).

The programmed Q(V) controllers with and without deadband determined the LV feeder voltage profile, as shown in Figures 7.9 and 7.10. However, these two figures had similar values for the maximum permitted solar PV generation (14 P/cluster) to that of using a fixed power factor control (Figure 7.7). This negligible difference could be because the deadband was relatively narrow.
Figure 7.9. 415 V Feeder Voltage Profile at Minimum Daytime Load with Increasing Solar PV Generation with the Implementation of the OL-VRDT and Q(V) with Voltage Deadband when the Solar Generation was 12 and 14 P/cluster, and with the Usage of the OL-VRDT when the Solar Generation was 12 P/cluster.

In other words, based on comparing these two reactive power controllers with the basic single OL-VRDT control, the maximum allowable solar PV generation could be increased by
2 P/cluster. This is better than the performance attained by using OL-VRDTs with LDC, as shown in Figure 7.6, which presented only 1 P/cluster growth. This means that the reactive controllers are more efficient in mitigating voltage rise than the LDC.

To maximise the benefits of the Q(V) controller on voltage control, Q(V) fulltime control needed to be examined. This control is independent of the solar condition and requires that active power can be injected from grids to provide necessary reactive power, which can effectively mitigate voltage drop during peak load demand periods at night. Assuming each cluster had a 14 P (132.21 kW) solar inverter, the fulltime ±Q limits would be 64 kvar based on ±Q capability when operating at rated power (132.21kW) and a power factor range of ±0.90 PF. The other settings for the Q(V) controller were kept the same, as mentioned above. The upper curve in Figure 7.11 shows the voltage profile of the fulltime Q(V) controller under the maximum load, with no solar condition. This curve shows that the voltage at the end of the LV feeder (0.982 pu) was higher than that determined in the base case condition (0.952 pu), which means that fulltime Q(V) controller can alleviate voltage drop and increase the load carrying capacity of LV feeders. This increased voltage is lower than the lower voltage limit of the voltage deadband of the Q(V) controller (0.99 pu ) as shown in Figure 7.8 which means that the Q(V) controller is delivering reactive power to increase voltages.
Figure 7.1. Voltage Profile for the 415 V Feeder under the Maximum Load Condition and No Solar (the Base Case) Condition (Bottom Curve) and the Condition with Implementation of the Fulltime Q(V) Controller (Upper Curve).

7.1.3.2 OL-VRDTs with LDC + Reactive Power Control of IES

In this scenario, none of the settings for the controllers from utilities or prosumers were changed. The following tables present the 415 V feeder voltage profile under different combination scenarios. Comparing the maximum solar PV generation under these conditions with the previous combined control without the implementation of LDC, the 1P/cluster solar generation increased. Therefore, these combination strategies had the best performance for mitigating voltage rise and increasing the penetration of PV systems in this study.

Table 7.2: 415 V Feeder Voltage Profile at the Minimum Daytime Load when the Solar PV Generation was at 14 and 15 P/cluster with Implementation of the OL-VRDT with LDC and Cos ψ (fixed)

<table>
<thead>
<tr>
<th>Solar Generation</th>
<th>MV DT</th>
<th>LV DT</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 P solar</td>
<td>0.996</td>
<td>0.962</td>
<td>0.978</td>
<td>1.015</td>
<td>1.034</td>
</tr>
<tr>
<td>15 P solar</td>
<td>0.996</td>
<td>0.96</td>
<td>0.979</td>
<td>1.019</td>
<td>1.039</td>
</tr>
</tbody>
</table>
Table 7.3: 415 V Feeder Voltage Profile at the Minimum Daytime Load when the Solar PV Generation was at 14 and 15 P/cluster with Implementation of the OL-VRDT with LDC and Q(V) Controller with Deadband

<table>
<thead>
<tr>
<th></th>
<th>MV DT</th>
<th>LV DT</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 P solar</td>
<td>0.997</td>
<td>0.962</td>
<td>0.98</td>
<td>1.016</td>
<td>1.034</td>
</tr>
<tr>
<td>15 P solar</td>
<td>0.997</td>
<td>0.961</td>
<td>0.98</td>
<td>1.019</td>
<td><strong>1.038</strong></td>
</tr>
</tbody>
</table>

Table 7.4: 415 V Feeder Voltage Profile at the Minimum Daytime Load when the Solar PV Generation was at 14 and 15 P/cluster with Implementation of the OL-VRDT with LDC and Q(V) Controller without Deadband

<table>
<thead>
<tr>
<th></th>
<th>MV DT</th>
<th>LV DT</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 P solar</td>
<td>0.997</td>
<td>0.961</td>
<td>0.979</td>
<td>1.016</td>
<td>1.034</td>
</tr>
<tr>
<td>15 P solar</td>
<td>0.997</td>
<td>0.959</td>
<td>0.979</td>
<td>1.018</td>
<td><strong>1.037</strong></td>
</tr>
</tbody>
</table>

OL-VRDT based control significantly increases the solar generation from 4.5P/cluster to the maximum 15P/cluster. This causes a significant reverse power flow on the distribution transformer and cables, therefore it is necessary to consider cables and the transformer are rated for that increased current.

**7.2 Analysis of Power Losses**

There are two power sources in this network: the AC voltage source and the PV generators. These sources inject power into the grids, which influences power flow and grid losses. The load flow analysis through PowerFactory determines the total load, generation and losses in distribution networks and the whole grid under different scenarios, which are listed in Appendices C, D, E and F. The main aim of this analysis was to examine the influence of different levels of roof solar PV generation and different voltage control strategies on network losses at the minimum load condition. The disadvantage of this 22kV/415V network is the PV systems, only installed at the end of feeder, cannot have a significant influence on the entire network. Therefore, it is necessary to analyse the power losses in both the LV grid and the whole grid.
7.2.1 Effect of Solar PV Generation on Grid Losses

Comparing the grid summary reports of the OL-VRDTs (with and without LDC) in Appendix C with the reports of the FT-DTs in Appendix D indicated that all the calculation results were the same under the same solar PV generation. To improve the accuracy of analysing the effect of solar PV generation, this examination used the scenario of implementing the OL-VRDTs with LDC. This scenario provided sufficient data under different solar generation cases for analysing the influence of solar generation on grid losses. In the 415 V network, Table 7.5 shows that the increase of solar PV generation caused increasing numbers of total losses, as grid losses are a function of current and impedance. The increased solar PV output meant an increased current; hence, the losses also increased. However, for the whole grid (Table 7.6), a higher penetration of solar PV systems leads to lower grid losses because the distribution generation gradually replaces the substation generation and avoided a large amount of power flow losses through transmission lines and transformers.

- 415 V Grid

Table 7.5: Key Information in Grid Summary Report Exported from DIgSILENT PowerFactory with the Increasing Solar PV Generation in 415 V Network

<table>
<thead>
<tr>
<th>Solar PV generation (P/cluster)</th>
<th>Grid summary</th>
<th>0</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total generation MW/Mvar</td>
<td></td>
<td>0.00/0.00</td>
<td>0.23/0.00</td>
<td>0.45/0.00</td>
<td>0.68/0.00</td>
<td>0.79/0.00</td>
</tr>
<tr>
<td>Total load MW/Mvar</td>
<td></td>
<td>0.06/0.04</td>
<td>0.06/0.04</td>
<td>0.06/0.04</td>
<td>0.06/0.04</td>
<td>0.06/0.04</td>
</tr>
<tr>
<td>Total losses MW/Mvar</td>
<td></td>
<td>0.00/0.00</td>
<td>0.00/0.00</td>
<td>0.01/0.00</td>
<td>0.03/0.01</td>
<td>0.04/0.01</td>
</tr>
<tr>
<td>Power interchanged from 415 V to 22 kV grid MW/Mvar</td>
<td></td>
<td>-0.06/-0.04</td>
<td>0.17/-0.04</td>
<td>0.38/-0.04</td>
<td>0.60/-0.05</td>
<td>0.70/-0.05</td>
</tr>
</tbody>
</table>
Whole Grid

Table 7.6: Key Information in Grid Summary Report Exported from DIgSILENT PowerFactory with the Increasing Solar PV Generation in the Whole Network

<table>
<thead>
<tr>
<th>Grid summary</th>
<th>Solar PV generation (P/cluster)</th>
<th>0</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total generation MW/Mvar</td>
<td>0.00/0.00</td>
<td>0.23/0.00</td>
<td>0.45/0.00</td>
<td>0.68/0.00</td>
<td>0.79/0.00</td>
<td></td>
</tr>
<tr>
<td>Total load MW/Mvar</td>
<td>4.40/3.29</td>
<td>4.40/3.29</td>
<td>4.40/3.29</td>
<td>4.40/3.29</td>
<td>4.40/3.29</td>
<td></td>
</tr>
<tr>
<td>Total losses MW/Mvar</td>
<td>0.05/-1.23</td>
<td>0.05/-1.23</td>
<td>0.06/-1.19</td>
<td>0.09/-1.13</td>
<td>0.11/-1.08</td>
<td></td>
</tr>
<tr>
<td>External infeed MW/Mvar</td>
<td>4.44/2.06</td>
<td>4.22/2.06</td>
<td>4.00/2.10</td>
<td>3.80/2.17</td>
<td>3.71/2.21</td>
<td></td>
</tr>
</tbody>
</table>
7.2.2 Effect of Different Technical Solutions on Grid Losses

This section examines the grid losses caused by the two reactive power controllers of the IES. This evaluation is based on comparing the losses resulting from using different technologies when the solar PV generation was 12 P/cluster, as shown in Tables 7.7 and 7.8. These tables indicate that the different devices demonstrated no significant difference in the resulting total losses. However, the last rows of Tables 7.7 and 7.8 indicate that the IES reactive power controllers required more reactive power from the grids with increased solar PV output than did the OL-VRDT. The Q(V) controller had a relatively lower demand for reactive power than did the \( \cos \psi \) (fixed) controllers, which meant that the Q(V) controllers absorbed less reactive power to control voltages and avoided larger utility investments in capacitor banks or STATCOMs for injecting reactive power.

- 415 V Grid

Table 7.7: Key Information in Grid Summary Report Exported from DlgSILENT PowerFactory with the Implementation of Different Voltage Rise Mitigation Approaches when the Solar PV Generation was 12 P/cluster in 415 V Network

<table>
<thead>
<tr>
<th>Category of devices</th>
<th>OL-VRDTs</th>
<th>OL-VRDTs with Q(V)</th>
<th>OL-VRDTs with ( \cos \psi ) (fixed) = -0.95</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>With deadband</td>
<td>Without deadband</td>
</tr>
<tr>
<td>Total generation MW/Mvar</td>
<td>0.68/0.00</td>
<td>0.68/-0.04</td>
<td>0.68/-0.05</td>
</tr>
<tr>
<td>Total load MW/Mvar</td>
<td>0.06/0.04</td>
<td>0.06/0.04</td>
<td>0.06/0.04</td>
</tr>
<tr>
<td>Total losses MW/Mvar</td>
<td>0.03/0.01</td>
<td>0.03/0.01</td>
<td>0.03/0.01</td>
</tr>
<tr>
<td>Power from 415 V to 22 kV grid MW/Mvar</td>
<td>0.59/-0.05</td>
<td>0.59/-0.08</td>
<td>0.59/-0.10</td>
</tr>
</tbody>
</table>
Whole Grid

Table 7.8: Key Information in Grid Summary Report Exported from DlgSILENT PowerFactory with the Implementation of Different Voltage Rise Mitigation Approaches when the Solar PV Generation was 12 P/cluster in the Whole Grid

<table>
<thead>
<tr>
<th>Category of devices</th>
<th>OL-VRDTs</th>
<th>Q(V)</th>
<th>Cos ψ (fixed) = -0.95</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With deadband</td>
<td>Without deadband</td>
<td></td>
</tr>
<tr>
<td>Total generation MW/Mvar</td>
<td>0.68/0.00</td>
<td>0.68/-0.04</td>
<td>0.68/-0.05</td>
</tr>
<tr>
<td>Total load MW/Mvar</td>
<td>4.40/3.29</td>
<td>4.40/3.29</td>
<td>4.40/3.29</td>
</tr>
<tr>
<td>Total losses MW/Mvar</td>
<td>0.09/-1.13</td>
<td>0.09/-1.13</td>
<td>0.09/-1.12</td>
</tr>
<tr>
<td>External infeed MW/Mvar</td>
<td>3.80/2.17</td>
<td>3.81/2.21</td>
<td>3.81/2.22</td>
</tr>
</tbody>
</table>

7.3 Summary

From a voltage management perspective, the best method can be summarised as the combination of the OL-VRDT with LDC and fulltime Q(V) control on PV inverters. This combination not only allowed the most solar PV generation, as shown in Table 7.9, but also supported the control of voltage at night to avoid extreme voltage drop along the radial feeder. In addition, Q(V) controllers reduced potential expenditure on capacitor banks and STATCOMs, compared to fixed power factor controllers. Therefore, this combination of methods can further extend the enhanced load carrying capacity provided by the voltage setpoint control of OL-VRDTs. However, there are some drawbacks to this method. First, it involves a complicated selection process for the parameters of OLTC and LDC, as introduced in Chapter 5, which requires careful control in the real world. Second, the reactive power controllers have additional demand for reactive power from grids, as discussed in Section 7.2. Therefore, utilities must justify different approaches before selection. If utilities are unwilling to inject more reactive power, the relatively better method to mitigate voltage rise is the use of OL-VRDT with LDC. In addition, if utilities are unsure whether they can successfully determine the LDC parameters, they can select the single OL-VRDT, which can easily control
the setpoint voltage of the OLTC. In addition, both OL-VRDT-based voltage control and fulltime Q(V) control can reduce voltage variations and increase the load carry capacity of the LV feeder, as found in Section 7.1.

Table 7.9: Summary of the Maximum Solar PV Generation under Different Implemented Approaches

<table>
<thead>
<tr>
<th></th>
<th>Prosumers</th>
<th>Reactive power control of IES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cos φ = 1</td>
<td>cos φ (fixed) = -0.95 (absorbing)</td>
</tr>
<tr>
<td>FT-DT</td>
<td>4.5 P</td>
<td></td>
</tr>
<tr>
<td>OL-VRDT</td>
<td>12 P</td>
<td>14 P</td>
</tr>
<tr>
<td>OL-VRDT with LDC</td>
<td>13 P</td>
<td>15 P</td>
</tr>
</tbody>
</table>

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Chapter 8: Conclusions

8.1 Key Findings of this Study

All of the selected advanced methods provided a better voltage rise mitigation capability than that of the FT-DTs. Analysing the summary sections in Chapters 5 and 7 indicated that the characteristics of the power grids had an influence on determining the effectiveness of different methods for alleviating voltage rise and the allowable amount of solar PV generation. The network in this project allowed for more solar PV penetration than did the previously studied network, which was caused by LV distribution networks with distributed PV systems not being modelled along the main 22 kV feeder in the SWIS, apart from the last bus. Also the loads on the representative LV feeder were lower than those used by Lu [7].

However, this difference in the power grid modelling did not influence the conclusion that the OL-VRDT with LDC was the best method from utilities in both Chapters 5 and 7, although this requires careful selection of the parameters Vset, Xset and Rset. The OL-VRDT controls voltage in the LV network by managing the voltage at the LV side of the MV/LV transformer. The OL-VRDT with LDC monitors the power flow along the LV feeder, and compensates the voltage drop or rise to better control LV voltages. The benefit of the voltage control using OL-VRDT with and without LDC is to make LV feeders accommodate more loads in distribution networks.

Chapter 7 outlined the advantages and disadvantages of the combination methods of the OL-VRDT (with and without LDC) and the two reactive power controllers of IES ($cos \varphi (fixed) = -0.95$ pf and $Q(V)$). Although these methods were more efficient in mitigating voltage rise than the single method from utilities, the inclusion of the reactive power controllers caused additional reactive power demand. The $Q(V)$ control absorbed relatively less Q, compared with
the fixed absorbing power factor controller. This is because the Q(V) controller, which has a reactive power range (±0.9 PF) that can absorb more reactive power than fixed -0.95 pf operation, only absorbs reactive power when voltages are high and outside the Q(V) controller’s voltage deadband (±1%). Fulltime Q(V) control is the most advanced method to be coordinated with the utility solutions. This combination can manage the voltage variation at night during the peak load period, as the Q(V) fulltime controller is independent of solar PV generation.

### 8.2 Recommendations for Future Studies

This research makes the following suggestions for future work to further explore approaches that can mitigate voltage rise to increase the penetration of rooftop PV systems. Firstly, future research can employ a more representative WA distribution network with detailed information on the connected LV distribution networks with rooftop PV systems. The reason is that this thesis is limited by the undetailed information of the 415V distribution network, which restricts the investigated methods to be applied in the real world. Secondly, future research can investigate ‘behind-the-meter’ battery storage systems, as introduced in Chapter 4. The focus of the research would be creating a strategy for a battery-charging regime. Thirdly, future research can apply a remote control (decentralized control) for selecting appropriate parameters for the line drop compensation controller and on load voltage regulation distribution transformer to maximize their ability to mitigate voltage rise.
Chapter 9: References


Glossary

**Charging rate**: A rate of charge in amperes that varies with the capacity of the battery [31].

**Distributed network**: LV(415V) network in this context.

**Harmonics**: The ‘sinusoidal component of a periodic wave or quantity [with] a frequency that is an integral multiple of the fundamental frequency’ [43].

**Local control**: This control requires no communication infrastructure in the network and each device can control itself using programmed information [13].

**PV penetration**: ‘The ratio of peak PV power to the peak load apparent power on the feeder’ [3].

**Prosumers**: Owners of distributed energy systems who not only consume energy but also return excess energy to the grid and/or to other consumers [2].

**Solar energy self-consumption**: Prosumers consuming the energy produced by PV panels.
Appendices

Appendix A: Operation of Reactor-type OLTC Tap Changer

Figure 10: Structure of the Reactor-type OLTC
Appendix B: Operation of Resistor-type OLTC Tap Changer

The switching sequence from Tap 1 to Tap 3 can be explained step by step:
1. Start at Tap 1 on the left side of the winding; the other switches need to be open; the diverter switch short circuits Resistor B.

2. Close the switch at Tap 2 under off-load conditions; the tap changer requires a new tap to be connected before releasing the old tap.

3. Move the diverter switch right towards the new tap (Tap 2) and Resistor B will limit the current during the switching.

4. Connect the diverter switch to both the A and B resistors.

5. Connect the diverter switch to Resistor A only.

6. Complete the tap change and short circuit Resistor A.

7. Open the switch at Tap 1.

### Appendix C: Grid Summary Report for FT-DTs under Different Solar Generation

<table>
<thead>
<tr>
<th>Grid: MGR Unit PHD</th>
<th>System Stage: MGR Unit PHD</th>
<th>Study Case: Study Case</th>
<th>Annex:</th>
<th>/ 1</th>
</tr>
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</table>

Figure C.1: Grid Summary Report when the Solar Generation is 0P/cluster
Figure C.2: Grid Summary Report when the Solar Generation is 2P/cluster

<table>
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<th>Study Cases: Study Case</th>
<th>Annex</th>
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<td>0.00</td>
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</tr>
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Figure C.3: Grid Summary Report when the Solar Generation is 4P/cluster

Appendix D: Grid Summary Report for OL-VRDT (with and without LDC) under Different Solar Generation

Figure D.1: Grid Summary Report when the Solar Generation is 0P/cluster
<table>
<thead>
<tr>
<th>Voltage</th>
<th>Generation</th>
<th>Motor Load</th>
<th>Load</th>
<th>Compensation</th>
<th>External Infeed</th>
<th>Interchange to</th>
<th>Power</th>
<th>Interchange</th>
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<th>MLoad Losses</th>
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<td>0.00</td>
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</table>

**Figure 12:** Grid Summary Report when the Solar Generation is 2P/cluster

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<th>Generation</th>
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<th>Load</th>
<th>Compensation</th>
<th>External Infeed</th>
<th>Interchange to</th>
<th>Power</th>
<th>Interchange</th>
<th>Total</th>
<th>Load Losses</th>
<th>MLoad Losses</th>
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**Figure D.3:** Grid Summary Report when the Solar Generation is 4P/cluster

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<th>Load</th>
<th>Compensation</th>
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<th>Interchange to</th>
<th>Power</th>
<th>Interchange</th>
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<th>Load Losses</th>
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**Figure D.4:** Grid Summary Report when the Solar Generation is 6P/cluster
Figure D.5: Grid Summary Report when the Solar Generation is 8P/cluster

Figure D.6: Grid Summary Report when the Solar Generation is 10P/cluster

Figure D.7: Grid Summary Report when the Solar Generation is 12P/cluster

Appendix E: Grid Summary Report for OL-VRDT with LDC and Fixed power factor (cos \( \phi \) (fixed)) under Different Solar Generation
Appendix F: Grid Summary Report for OL-VRDT with LDC and Q(V) control (with and without deadband) under Different Solar Generation

Figure E.1: Grid Summary Report when the Solar Generation is 12P/cluster

<table>
<thead>
<tr>
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<th>Motor Load ([kW])</th>
<th>Motor Load ([kVAR])</th>
<th>Load Comp. ([kW])</th>
<th>Load Comp. ([kVAR])</th>
<th>External Load ([kW])</th>
<th>External Load ([kVAR])</th>
<th>Interchange to ([kW])</th>
<th>Interchange to ([kVAR])</th>
<th>Power Interchange ([MW])</th>
<th>Power Interchange ([MVAR])</th>
<th>Total Losses ([kW])</th>
<th>Total Losses ([kVAR])</th>
<th>Load Losses ([kW])</th>
<th>Load Losses ([kVAR])</th>
<th>Hub Load Losses ([kW])</th>
<th>Hub Load Losses ([kVAR])</th>
</tr>
</thead>
</table>
Figure F.2: Grid Summary Report for the Q(V) Control without Deadband when the Solar Generation is 12P/cluster.