An investigation into voltage control strategies on an A1 distribution network with increased PV power generation

ENG470 Engineering Thesis project

By

Ningbo Li

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Supervisor: Gregory Crebbin
Abstract

PV generation has become one of the most important renewable energy productions in the world. This clean and natural source of energy could be a key to solve the worldwide energy crisis with low environmental impact. The increased penetration of PV generation into the power grids mean the impact of PV power on the electricity network can no longer be ignored. However, high PV penetration into the LV feeders may result in some negative effects regarding to the stability of the distribution networks. One consequence is that voltage rise problem in distribution feeder caused by a coincident of a high PV generation and a low load demand. Various centralized and local control strategies have been the subject of several investigations to address this problem. One particular area is focus on the potential of PV inverters to manage the voltage profile of the distribution network by injecting the reactive power for the grid. Several strategies for reactive power support have been presented to solve this problem. This can be achieved by using different relationships between the VAR power and feeder voltage output. In addition, active power generation from PV system can be directly constrained to prevent voltage rise issue using Maximum Power Point Tracking (MPPT) from PV inverters.

A strategy for voltage regulation investigated recently is to incorporate the power electronic tap changing into the LV distribution transformer. It is a high speed voltage control mechanism that the voltage profile in the LV distribution feeder can step change on a 50Hz at half-cycle intervals. A simple algorithm provides the feeder voltage regulation function by transformer tap changing, and then varies the transformer tap position as the power flow through the distribution transformer changes to keep the voltage profile along the feeders within the regulatory limits. This can be confirmed by a series of simulation studies on the distribution feeders under various PV generation injections, daily load demand. Software packages (e.g. DIgSILENT PowerFactory) will be used throughout the thesis. Other voltage control strategies using PV inverters will be confirmed in this simulation study as well. An evolution of a combined strategy will be investigated and some suggestions for the future works will be presented at the end of the thesis.

Keywords: voltage rise issue, voltage control strategies, distributed PV generation.
Acknowledgements

I would like to thank my project supervisor, Dr Gregory Crebbin, for his kind and continuous help, patience, encouragement and supervision of this thesis project. I would also like to thank all those people and friends who gave me support and helped me towards the completion of my thesis. Without them, this project could be more difficult and challenging.
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# Glossary

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<thead>
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<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>LV</td>
<td>Low voltage</td>
</tr>
<tr>
<td>HV</td>
<td>High voltage</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
</tr>
<tr>
<td>DNOs</td>
<td>Distribution Networks Operators</td>
</tr>
<tr>
<td>VAR</td>
<td>Volt-Ampere Reactive</td>
</tr>
<tr>
<td>RPM</td>
<td>Reactive Power Management</td>
</tr>
<tr>
<td>SPC</td>
<td>Solar Power Curtailment</td>
</tr>
<tr>
<td>Over-voltage</td>
<td>When voltage exceeds required limits</td>
</tr>
<tr>
<td>Under-voltage</td>
<td>When voltage is below required limits</td>
</tr>
<tr>
<td>OLTC</td>
<td>On-Load Tap Changer</td>
</tr>
<tr>
<td>SCR</td>
<td>Silicon-Controlled Rectifier (thyristor)</td>
</tr>
<tr>
<td>DG</td>
<td>Distribution generation</td>
</tr>
<tr>
<td>PF</td>
<td>Power Factor</td>
</tr>
<tr>
<td>Australian Standard</td>
<td>AS</td>
</tr>
<tr>
<td>Peta Joules</td>
<td>PJ</td>
</tr>
<tr>
<td>pu</td>
<td>Per-unit</td>
</tr>
</tbody>
</table>
1. Introduction

The recent increases in green energy production are causing a gradual replacement of conventional fossil based generation by renewable energy generation. One renewable energy generator that has attracted considerable attention in recent years is the interconnected array of photovoltaic cells, because a PV array can provide a clean and inexhaustible energy resource that does not produce greenhouse gases and is therefore friendly to the planet and to humanity [1]. Distribution Network Operators (DNOs) who manage networks have raised concerns regarding the impact of high penetration levels of PV generation into distribution networks. The most severe consequence is that the reversal of the power flow caused by large amounts of PV power generated from residential rooftop PV panels may produce voltage rise issue to which the DNOs control for traditional voltage regulation approaches become less effective [2].

PV power generation peaks during the day while the residential load demand is usually at its lowest value, and so power flows in the reverse direction from the end of the feeder (the customer) to the utility grid (the conventional supplier). This can cause over-voltages along the feeder if the tap of the distribution transformer is set too high. On the other hand, in the evening, the load demand can be high while PV generation is low, which can cause under-voltages along the distribution feeder if the tap setting for distribution transformer is too low. Typically, a traditional tap changer is not able to cope with the voltage variations.

Another consequence is when clouds sweep over areas with large concentrations of PV generation, which can cause large and sudden variations in the PV power output, hence causing voltage instability in the distribution network.

In Australia, DNOs have already presented some strategies to manage the voltage rise effects in distributed networks with grid-connected PV systems by limiting the installed capacity of PV power generation on distribution feeders and requiring PV inverters to operate at unity power factor. The PV Inverters are not allowed to provide any primary voltage control support to avoid adverse interactions between conventional voltage control technologies, such as mechanical OLTC and reactive power support from PV inverters [3]. However, this conservative strategy is not based on any substantive technical assessment and is done more as a matter of expediency to avoid large disturbances in distribution feeders. This is clearly not a long term solution as PV generation levels will continue to increase, and the voltage fluctuation caused by rapid change in PV power output will become more significant.
In response to these issues, both centralized and local voltage control approaches have been proposed for voltage rise mitigation with high PV production. Local approaches have been proposed that allow for a reactive power injection from PV inverters. Most DNOs require PV generation to operate at zero reactive power injection, but there is an increasing recognition of the potential for these PV inverters based to inject (absorb) reactive power into the grid to manage the voltage profile of distribution feeders. Kabiri presented an investigation of several reactive power control strategies using PV inverters on the daily voltage profiles of LV feeders in Australia, when subjected to high PV penetration levels [4]. Other dispatching schemes have been considered for voltage regulation through the real power curtailment from distributed PV generation. Jonkoski proposed a coordinated active power curtailment of PV inverters for overvoltage prevention to improve the operational performance of distribution networks [5]. These local control methods for PV inverters can have some effect on voltage profile of LV feeders, which can be seen by the DNOs. However, such local schemes cannot guarantee an optimal voltage profile of distribution network because they are not able to have access to the entire distribution feeders.

A recent method for centralized voltage regulation incorporates a power electronic tap changer into the primary distribution transformer of the feeders [6]. Its functionality allows the supply voltage profile to be increased or decreased on a cycle by cycle basis due to continuous tap changing. The capabilities of rapid acting tap changers can be used as a primary voltage control mechanism in order to mitigate voltage fluctuation effects caused by a sharp change in PV power output.

This thesis proposes a voltage control strategy for an A1 distribution network with increased PV power generation that uses an electronic transformer tap changer. A literature review for this thesis are given in chapter 2, which includes Australia’s solar energy resource, PV installation status and an investigation into the voltage fluctuation of distribution networks with different feeder characteristic parameters, such as penetration levels of PV generation and daily load consumption. Chapter 3 presents an approach of modeling the A1 distribution network and simulation in DigSILENT’s PowerFactory, version 15.2. A description of the network components is also included in this chapter. In chapter 4, a theory of the centralized voltage control method for the electronic transformer tap changer will be described. Two small case studies associated with voltage fluctuation effects will be carried out with PowerFactory, and then the transformer tap changer model will be implemented and assessed. In chapter 5, the results of this thesis will be presented. Voltage profile performance of the A1
distribution network with increased PV generation will be studied using PowerFactory. The performance of the voltage rise mitigation using electronic tap transformer changer in the A1 distribution network will be presented and analyzed. In chapter 6, other control strategies will be presented for managing the voltage rise issue, and the algorithms will be evaluated using detailed simulations of the A1 distribution networks that are subject to a wide range of PV generation levels. Chapter 7 discusses combined strategies between these voltage regulation methods, and will provide a useful strategy to improve the operational performance of the distribution network. In the last section, the thesis will be concluded and some recommendations for future works will be outlined.

1.1 Aim of this thesis

This thesis investigates the voltage profile regulation of the A1 distribution network with increased penetration levels of PV generation. The first objective is to clarify the impact of high PV power generation on the voltage profile in the distribution network. A better understanding will focus on voltage rise and voltage fluctuation issues caused by variations in PV power output from residential rooftop PV panels.

The second objective is to investigate the coordinated electronic tap changer for a distribution transformer, which is proposed to mitigate the negative effects. The objective will be met by carrying out a series of simulation studies over a wide range of PV penetration levels using PowerFactory.

The third objective is to assess several other voltage control strategies to draw more quantitative conclusions with respect to the impact of increased PV generation on voltage rise.

The fourth objective is to investigate hybrid strategies between the separate voltage regulation strategies in order to achieve the optimal voltage regulation.

1.2 Description of the A1 distribution network model

This network is a representation of a residential area which consists of an external 132kV grid, substation, transformers, and six main zones of 400V LV distribution feeder lines,
including the loads and PV systems of each bus. Specifically, external power is supplied through a 20MVA 132/22kV transformer from the substation. The 22kV transmission line has been integrated with six 630 KVA 22kV/400V distribution transformers connected on the 22kV side, with 0.5km intervals between them. Each transformer has been connected to a 400V LV distribution feeder. There are 4 buses in each 400V feeder, with each bus representing 60 houses at distances of 100m, 200m and 300m from the 22kV/400V distribution transformer. The single line diagram for the network is shown in Figure 1.

Figure 1: The configuration of the A1 distribution network within PowerFactory software package
1.3 Announcement

The system model within this thesis has been referred to as the A1 distribution network due to abundant research on the residential rooftop PV system and case study for modeling a distribution system. In order to investigate the voltage rise issue due to high PV penetration, I make changes to the system model based on the previous case studies which were proposed in [6] and [7]. This is a copyright issue: "I have been given permission by the authors to use their model data in this simulation”. This will be referred to from now on as the A1 distribution network.
2. Background and literature review

2.1 Australian solar energy resources and PV status

2.1.1 Solar energy resources in Australia

Australia has a very high potential for solar energy resources. The annual solar radiation (in MJ/m²) is an average 58 million PJ, which is approximately 10000 times larger than Australia’s annual energy consumption [8]. It should be noted from Figure 2 that solar energy resources are greater in the Northwest and center of Australia, but they do not have access to the national electricity grid because of limited transmission lines. However, there are also a large amount of solar energy resources in southeast of Australia with access to the power grids.

![Australian average solar radiation (in MJ/m²) and installed capacity of solar power stations per year](image)

Figure 2: Australian average solar radiation (in MJ/m²) and installed capacity of solar power stations per year [8]

2.1.2 PV installation status in Australia

There are numbers of larger-scale PV power stations with a capacity of more than 100 kW in Australia, which are dedicated to individual markets. For example, The Alice Spring power plant is a small 'island' grid which provides power to the greater Alice Spring area, and remotely up to 100km from the town center. The network sees a peak demand of 55MW in the summer months and meets the demand through a range of generators distribution across
the network [9]. However, small-scale rooftop PV installations are common in the majority of Australia. The annual energy production by a rooftop PV system depends on the rated PV output and the geographic location. Table 1 shows a summary of small-scale PV generation forecast in Australia.

Table 1: A summary of small-scale PV generation forecast in Australia in December 2015[10]

<table>
<thead>
<tr>
<th>State</th>
<th>Percentage of dwellings with a PV system by State/Territory (%)</th>
<th>Installed PV generation capacity by State /Territory (MW)</th>
<th>Annual energy generated from PV by State /Territory (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QLD</td>
<td>29.1</td>
<td>1379.7</td>
<td>93.6</td>
</tr>
<tr>
<td>SA</td>
<td>28.4</td>
<td>558.3</td>
<td>83.1</td>
</tr>
<tr>
<td>WA</td>
<td>21.9</td>
<td>474.4</td>
<td>68.4</td>
</tr>
<tr>
<td>NSW</td>
<td>13.8</td>
<td>812.6</td>
<td>322.7</td>
</tr>
<tr>
<td>VIC</td>
<td>13.8</td>
<td>769.3</td>
<td>98.9</td>
</tr>
<tr>
<td>ACT</td>
<td>12.8</td>
<td>49.7</td>
<td>28.5</td>
</tr>
<tr>
<td>TAS</td>
<td>11.8</td>
<td>79.3</td>
<td>10.3</td>
</tr>
<tr>
<td>NT</td>
<td>8.2</td>
<td>18.1</td>
<td>10.6</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>4141.4</td>
<td>761.1</td>
</tr>
</tbody>
</table>

2.2 The impact of PV penetration on voltage profile in distribution network

2.2.1 Voltage rise issue

Considering a simple two-bus system where the voltage rise ($\Delta V$) due to distributed PV integration is given by [11]:

$$\Delta V = \frac{PR + XQ}{V}$$

where $P$=active power injection
Q= reactive power injection
R= resistive of the transmission line
X= inductive reactance of the transmission line
V= nominal voltage

In some cases, a PV inverter operates at a unity power factor with maximum power \( P_{\text{max}} \), and the voltage rise \( \Delta V_1 \) at the maximum allowed voltage \( V_{\text{max}} \) of the feeder end bus has

\[
\Delta V_1 = \frac{P_{\text{max}} R}{V_{\text{max}}} \quad \text{......................................................... (2)}
\]

If one wishes to further increase the amount of PV power injection, it may cause reverse power flow up to the utility grid thoroughly at a LV distribution level. This situation often manifests itself in voltage rises along the feeders, since additional power will flow from the distribution system to the transmission system. The most severe disturbances occur when the PV power output peaks while the residential neighborhoods are at the lowest level of the load demand, it will result in voltage rise at its highest level.

2.2.2 Voltage fluctuation due to the cloud-induced transient

The weather and the solar irradiation conditions are uncertain during the day, which leads to uncertain variation in PV power generation. The most severe transient disturbance in the PV power output would probably be encountered when clouds sweeps over an area that has a large concentration of PV generators. This could result in sudden variations in the PV power output, and hence cause the voltage fluctuations in the distribution network.
2.2.3 Operational Limits of LV feeders in Australia

A new voltage level, AS 60038-2000, was introduced during February 2000. It is 230 / 400 V ranged from +10 % to -6 %. In addition, within the installation the Wiring Rules allow up to a 5 % voltage droop due to the line impedance. This adds to the lower tolerance and extends the required utilization range for equipment. The utilization range becomes +10 % to -11 % [12], as shown in Table 2. For a steady-state operation, a voltage range between 0.89pu and 1.1pu is permitted and will be used as a benchmark in this investigation.

<table>
<thead>
<tr>
<th>System voltage</th>
<th>Supply range</th>
<th>Installation volt drop</th>
<th>Total voltage range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Australia to AS 2926-1987</strong></td>
<td>240/415V</td>
<td>-6% to +6%</td>
<td>-5%</td>
</tr>
<tr>
<td><strong>Australia to AS 60038-2000</strong></td>
<td>230/400V</td>
<td>-6% to +10%</td>
<td>-5%</td>
</tr>
<tr>
<td><strong>IEC 60038:1983</strong></td>
<td>230/400V</td>
<td>-10% to +6%</td>
<td>-4%</td>
</tr>
<tr>
<td><strong>Combined range for universal product</strong></td>
<td>230/400V</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. Network modeling approach and simulation in PowerFactory

This chapter discusses the approach to the modeling of the A1 distribution network with distributed PV generation. For this purpose, data collection from several sources will be investigated first. The data collected is discussed as well as the construction of the PowerFactory model. Then, the models for the network components, such as cables and transformers, created within PowerFactory to represent the A1 distribution network are discussed briefly. All the network component parameters within the PowerFactory model created by this thesis can be found in appendix B. Finally, the effects of variation on PV power outputs and daily load demand will be considered.

3.1 Data collection

Data for the PowerFactory model was collected from a number of sources. Specifically, the feeder modeling has taken into account Australian Standard voltages AS 60038-2000. It provides a new system voltage level that was described briefly in section 2.2.3. The 400V LV distribution feeder data is taken from [6] and the 22kV HV transmission line data is provided by [7]. These two papers specify typical transformers and cables parameters for LV and HV systems respectively. Positive and zero sequence resistance and reactance for cables were extracted and used in PowerFactory to create an accurate representation of the cables in the distribution network. Short circuit voltage and copper losses for the transformers were extracted from these papers as well.

3.2 Network component models

3.2.1 External grid

An external grid element from the PowerFactory library was used to model the transmission network feeding the substation. The symbol for this element is shown in Figure 3.
Specifically for the Al distribution network, the external grid model simulates a 132kV transmission network. The purpose of this grid element is to deliver electricity into the Al distribution network whenever there is negative PV power injection for the residential load.

3.2.2 Two winding transformers model

There are two types of transformer models within the PowerFactory library that will be used in the distribution network. The Delta – Delta model is used for the 200MVA 132/22kV substation transformer, and the Delta – star neutral model is used for the connection of the 400V LV distribution feeders to the Al distribution network.

(i) 630 KVA 22KV/400V distributed transformer

Figure 4 shows the symbol for the Delta – star neutral transformer model. On the high voltage side, the distribution transformer with a delta primary is running on three 22 kV phases with no neutral or earth required. While, on the low voltage side, this configuration has its star point connected to ground and the neutral wire providing a 3-phase supply at 400 V, with the phase voltage of 230V available across each phase.

(ii) 20MVA 132/22kV substation transformer

Figure 5 shows the Delta – Delta transformer model. This configuration has no neutral as the HV network is delta configuration.
Within the distribution transformers, the parameters are specified in Table 3.

Table 3: A summary of transformer data in the A1 distribution network

<table>
<thead>
<tr>
<th>Parameter</th>
<th>132/22kV station transformer</th>
<th>22kV/400V Distributed Transformer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power rating</td>
<td>20MVA</td>
<td>630kVA</td>
</tr>
<tr>
<td>Transformer type</td>
<td>Dd</td>
<td>Dyn</td>
</tr>
<tr>
<td>Frequency</td>
<td>50Hz</td>
<td>50Hz</td>
</tr>
<tr>
<td>Max tap position</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Min tap position</td>
<td>-10</td>
<td>-10</td>
</tr>
<tr>
<td>Voltage per tap</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Copper loss</td>
<td>0kW</td>
<td>3kW</td>
</tr>
<tr>
<td>Short-circuit voltage</td>
<td>6%</td>
<td>3%</td>
</tr>
</tbody>
</table>

3.2.3 Cable model

Figure 6 shows the line model used to represent different feeder cables within the PowerFactory. Each cable is defined by various parameters. The HV lines use 240mm², 22kV, underground copper cables to represent the 22kV feeder cables, and the LV lines use 70mm², 400V, underground copper cables to represent the 400V LV feeder cables. Within the line models, the parameters are summarized in Table 4.
Table 4: A summary of line impedance parameters in the A1 distribution network

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HV line cable</th>
<th>LV line cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage (Line to line)</td>
<td>22kV</td>
<td>400V</td>
</tr>
<tr>
<td>Crossection</td>
<td>240mm²</td>
<td>70mm²</td>
</tr>
<tr>
<td>Material</td>
<td>Copper</td>
<td>Copper</td>
</tr>
<tr>
<td>Length</td>
<td>500m</td>
<td>100m</td>
</tr>
<tr>
<td>Resistance</td>
<td>0.161 ohm/km</td>
<td>0.27 ohm/km</td>
</tr>
<tr>
<td>Reactance</td>
<td>0.067 ohm/km</td>
<td>0.0735 ohm/km</td>
</tr>
<tr>
<td>System type</td>
<td>AC</td>
<td>AC</td>
</tr>
</tbody>
</table>

3.2.4 General load model

Figure 7 shows the balanced three phase load model implemented in this simulation study. This model is used to represent pure resistive loads such as incandescent lamps and heating elements.

![Figure 7: Balanced three phase load model [13]](image_url)
3.3 Variations in load and supply

Variations in load demand and solar availability will need to be considered by the simulation studies.

1) The load is variable
Systems rarely have perfectly balanced loads in all three phases, because the load consumption varies in different residential neighborhoods. Sometimes if a load consumption of one user is connected to one phase that has a very low load demand, it will create an unbalanced three phase load at each bus. However, the system is assumed to be balanced in this project. This can be coordinated by switching 60 customers at each bus to create a more balanced three phase load.

In addition, the load consumption of one consumer is variable over 24 hours. Figure 8 shows a typical daily PV output and load profile of one customer during a typical sunny day. It can be clearly noted that the maximum load consumption of this house is about 1.1 kW during the evening while the minimum value is 0.4 kW during the day time. Each bus represents 60 house clusters. We assume that the daily load consumption for each bus ("60 house clusters") is the same. Therefore, the input data for the load consumption at each bus is shown in Table 5. Only worst cases scenarios are analyzed throughout this thesis.

Table 5: A summary of the maximum and the minimum load demand operated at unity power factor

<table>
<thead>
<tr>
<th>Load demand condition</th>
<th>Active power</th>
<th>Power factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum load consumption</td>
<td>60 kW</td>
<td>1</td>
</tr>
<tr>
<td>Minimum load consumption</td>
<td>24 kW</td>
<td>1</td>
</tr>
</tbody>
</table>

2) PV Generation is uncertain
It can be clearly noted form Figure 8 that the PV power output increases up to a maximum power point (seen in 3.4 kW at each house) at noon time while there is no PV power generation during the early morning and night time. In addition, the weather and the solar irradiation conditions are uncertain during the daytime, which leads to temporary reduction in PV power generation. For example, clouds covering the sun can reduce the energy absorbed by a PV panel depending on how much daylight they diffuse. The effect of clouds in the
daytime depends upon cloud type. Thin clouds absorb less sunlight so their net effect is an approximately 10% reduction in solar radiation absorption while thick clouds may obscured a significant amount of sun irradiation (up to 45% reduction) [14].

Figure 8: The PV generation and load profile of one user during a typical sunny day [6]
4. Electronic Transformer Tap Changers

This chapter discusses a centralized control method available to a distribution substation that uses an electronic transformer tap changer in order to keep the network voltages within a required range. In this case, we assume an automatic On-Load Tap Changing (OLTC) is available for the primary substation transformer to provide voltage regulatory support.

4.1 Traditional transformer tap changer

Traditional tap changers for distribution transformers are mechanical devices that can switch between tapped outputs of a transformer winding to change the effective transformer turns ratio and hence its output [15]. Traditional tap changer can be "off-load" when the tap changing is done manually, while the distribution transformer needs to be de-energized for secure operation reasons. This will result in a transient short current, because there is no induced current through the transformer during the tap changing. In addition, the tap changer can also be "on-load". The OLTC can maintain a continuous path for load current without creating a short circuit current between the taps, but they also require several seconds to change taps and there are high total $I^2R$ power losses during the changes. Therefore, the mechanical tap-changer is slow, non-contiguous and step-by-step. These limitations may not be able to satisfy for rapid voltage control. For example, voltage fluctuations due to cloud-induced transient may not be well resolved.

4.2 Distribution transformer electronic tap changer

Electronic tap changing systems are a relatively new technology that incorporates back to back Silicon Control Rectifiers (SCRs) as electronic switches instead of mechanical tap changer into the LV distribution transformer as shown in Figure 9. They offer very significant advantages compared with the traditional tap changers [16]. Firstly, there are no moving parts in the electronic tap changer systems, and the switching noises also reduce during the tap changing process because of no connection between the taps. In addition, it has an ability to step change at the zero crossing of the load current without creating any circulating current
and increased $I^2R$ power losses. Secondly, SCR switches provide a high speed tap change. So it is possible to change the tap repeatedly at half-cycle intervals with each new zero crossing. This capability makes them more attractive for high speed voltage regulation applications, such as mitigating the voltage fluctuation in distribution feeders caused by rapid changes in PV power output.

![Figure 9: The Circuit diagram of electronic transformer tap changer using SCRs [17].](image)

### 4.3 The principle of Power electronic tap changers

The SCR switching sequence for an electronic tap changer requires careful timing to avoid excessive circulating currents, when managing a fast voltage regulation in LV distribution feeders [6]. There are different sequences of tap change for different load characteristic (resistive/inductive/capacitive). The principles of the electronic tap changer will be described by using the inductive load example. Figure 10 shows the characteristics of a tap down transition for an inductive load.

To begin a tap changing sequence, the outgoing SCRs (S1 and S2) should be switch off before the load current crosses zero. According to the characteristic of a SCR, once it is switched on, or in other words when the anode current of the SCR switch is above the latching current, the gate losses control over it [18]. That means the gate circuit cannot turn off the device. The SCR switch will turn off when its anode current falls below the holding current. Therefore,
the load current continues to flow through the forward conducting SCR 1, while the incoming SCR 3 turns on just before the end of the cycle, and smoothly picks up the load current as it transitions through the zero crossing without producing excessive circulating current between the taps. Considering one case (i.e. the traditional tap changer) if the tap changing sequence is operating after the SCR1 is turned off. The incoming SCR 3 will start conducting over a very tiny region (Delay time of SCR and Delay time) after application of its gate current. This will lead to a low speed tap changing.

Figure 10: The characteristics of the tap down transition for an inductive load [3].
4.4 The deviation of voltage control using transformer tap changing

Figure 11 is a simple two-bus representation of a distribution feeder from bus i to bus j, fed from a MV slack bus through a variable tap distribution transformer. This model will be used to analyze the voltage profile of a distribution feeder for two worst case scenarios.

![Figure 11: A simple model of power transmission between two buses](image)

Representing the feeder line impedance \( Z = R + jX = Ze^{j\theta} \), the real and reactive power injection into the distribution feeder from the sending end is given by:

\[
S = V_i \left( \frac{V_i - V_j}{R + jX} \right) = \frac{V_i V_j}{Z} e^{-j(\theta_j - \theta_i)} - \frac{V_j^2}{Z} e^{j\theta} \tag{3}
\]

Separating (3) into real and reactive power components gives:

\[
\begin{align*}
P & = \frac{V_i V_j}{Z} \cos(\delta - \theta) - \frac{V_j^2}{Z} \cos(\theta) \\
Q & = \frac{V_i V_j}{Z} \sin(\delta - \theta) - \frac{V_j^2}{Z} \sin(\theta) \tag{4}
\end{align*}
\]

where \( \delta = \phi_j - \phi_i = \) power angle across the feeder line.

For a given real power injection (i.e. PV power injection), the voltage at the end Bus j can be calculated by rearranging (4) to give

\[
V_j = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{5}
\]

where \( a = -\frac{\cos(\theta)}{Z}, \ b = \frac{V_i}{Z} \cos(\delta - \theta), \ c = -P \)

From this understanding, a simple voltage regulation strategy can be proposed, which summarized as follow:

1) At the start of a control cycle, the bus j voltage is found by using equation (5), which depends on an active power output from PV systems.
2) There are three possible tap alternatives (high /neutral point /low) that can be used in the feeder transformer. Specifically, if the end bus voltage is above 1.1pu, the transformer tap is decreased by taking sufficient steps to lower it below 1.1pu. If this voltage is below 0.89pu, the transformer tap is increased by taking sufficient steps to raise it above 0.89pu. The required size of the tap step can be determined by using equation (5), and then the tap setting depends on a given change caused by each step to the feeder end bus voltage. For example, each tap position up or down results in a 1.5% change in the bus bar voltage. Thus, if the voltage was 1.0pu, and the tap position changed from the neutral position (zero) to tap ±1, then this would result in a voltage of 1.015pu or 0.085pu.
A simple algorithm for electronic tap changer is showing in Figure 12.

Figure 12: the voltage control algorithm using transformer tap changer [5]
4.5 The representation of the 400V LV individual distribution feeder

Consider one of the six main zone 400 V distribution feeders in the A1 network, which can be used to assess the effectiveness of the rapid acting tap changer. Figure 13 shows the representation of the 400V LV distribution feeder, which was described in detail in chapter 1.2. The external grid is represented by a grid element of a 22kV bus. Two small case studies will be modeled within the PowerFactory to illustrate the voltage regulation performance of the electronic tap changer. Firstly, a voltage rise issue caused by an increased PV power injection from residential rooftop PV panels will be determined. In this case, the static behavior of the 400V LV feeder can be modeled using the minimum daytime load consumption, and increasing the PV power injection from 0kW to the maximum power point (3.4kW) at each house. Secondly, voltage fluctuations could result in fairly large and sudden variations in the PV power output hence in the feeder voltage change. In this case, the dynamic behavior of the PV power output from the residential rooftop PV panel and load demand can be modeled over 24 hours based on the data given in Figure 8.

All the data information can be found in chapter 3.2, and the experimented setup within PowerFactory given in appendix B.

Figure 13: The representation of the 400V LV distribution feeder
Case 1: Voltage rise due to high PV penetration

Figure 14 shows the voltage profile of the LV distribution feeder without electronic tap changer, and Figure 15 shows the voltage profile with tap changing.

![Voltage profile of LV feeder without tap changer](image)

**Figure 14:** The feeder voltage profile without electronic tap changer
It should be noted from Figure 14 that there is a steady rising in voltage profile along the distribution feeder, with increasing feeder voltages output as the PV power injection increases. Without the electronic tap changer, voltage output at feeder buses 3 and 4 exceeds the regulatory limit when the PV power injection is over 3kW per house. Also, it can be noted from Figure 14 (the line for the maximum PV power injection) that the voltage output rises at its highest level when the PV power output peaks, which results in the worst case scenario for the LV distribution feeder.

Figure 15 shows the voltage profile with transformer tap control in the 400V distribution feeder. It can be clearly seen that all the voltage profiles in the LV feeder are now well controlled. Even the maximum PV power injection will be achieved without the over-voltage issue by stepping down the tap position as the DG increases.

The result from case 1 illustrates rapid adaptive tap changer offers an effective voltage control mechanism that permits a substantial increase in the maximum allowed PV penetration without voltage regulation issues, and without requiring the manual tap changes.
Case 2: Voltage fluctuation due to rapid change in PV power output

Figure 16 shows the dynamic voltage profile at end bus 4 with and without electronic tap changer over 24 hours.

This case presents a voltage regulation performance as the dynamic behavior of PV generation and residential load demand varies over 24 hour period. It can be noted from Figure 16 that the voltage profile at feeder end bus 4 fluctuates significantly as the PV power output changes without tap changing and at some moments exceeds the required limit of 1.1pu. Figure 16 also illustrates how the electronic tap changer changes the position in response to rapid changes in the PV power output over a 24 hour period in order to maintain the voltage profile at the feeder end bus 4 still within the regulatory limits. With an electronic tap changer, the voltage profile at the feeder end bus 4 is easily constrained to remain within the
limits at all times. Even the voltage output at its highest voltage rise level can be well controlled without an over-voltage problem.

The results from case 2 illustrate that this centralized voltage regulation minimizes the voltage fluctuations at the entire distribution feeders, but it is not enough economic justification since it requires feedback of each bus voltage. Also, it can be noted that this dynamic regulation cannot be achieved by conventional mechanical OLTC since rapid action is required to change taps at half-cycle intervals. Therefore, an electronic tap changer offers a significant advance in dynamic voltage regulation for LV distribution feeders, and it can support substantial penetration of DG resources.
5. Voltage rise mitigation using electronic tap changers

This chapter discusses the voltage rises due to increased PV penetration will be presented for the A1 distribution network. The coordinated electronic tap changing is integrated into the distribution transformer to confirm its effectiveness in reducing the voltage rises.

5.1 The base case scenario for voltage control investigation

The aim of simulating a base case scenario is to determine the impact of PV generation on the voltage profile of the A1 distribution network with increased PV power generation prior to the introduction of voltage control strategies.

In this base case scenario, each LV distribution feeder has four “60-house clusters” spaced at 0.1km intervals. The load consumption of each house is set to a minimum value of 0.4kW, making a total load of 24 kW at each “60-house cluster”, and there is an increased PV power generation from 0 kW to 1kW, 2kW and finally the maximum power output (3.4kW). It is assumed that load consumption is constant.
5.1.1 The result presentation for the base case scenario

Figure 17 shows the voltage profile of the A1 distribution network as the PV generation increases.

Figure 17: The voltage profile of the typical distribution network as the level of PV injection increases.
5.1.2 Discussion

Figure 18 illustrates the voltage level at the end bus 4.

![Diagram of voltage profile at the feeder end bus 4 at zone 6 with increased PV generation and the minimum load demand.]

Figure 18: The voltage profile at the feeder end bus (Zone 6 bus 4) as the PV generation increases in the A1 distribution network.

According to the operational limits for LV networks in Australia, a voltage range between 0.89pu and 1.1pu is considered acceptable for the grid supply. It can be clearly seen in Figure 17 that the feeder voltage steadily increases from the distribution transformer to the feeder end-bus as the level of PV power injection increases. When there is no PV power generated, the distributed network can operate without voltage problems. When the PV power injection is less than 2kW from each house, the voltage levels is always below 1.1p.u. The voltage profile at end bus 3 and 4 exceed regulatory limits when the power injection exceeds 3kW from each house. It should be noted from Figure 18 that the maximum PV power injection results in the most severe voltage rise problem, making this the worst case scenario. This centralized voltage control strategy for the electronic transformer tap changer will now be involved in an attempt to keep the voltage in the acceptable range even at the maximum PV penetration.
5.2 The implement of the electronic transformer taps changer

5.2.1 The simulation study using PowerFactory

The effectiveness of the electronic tap changer for mitigating voltage rise in the A1 distribution network will now be investigated. The settings can vary between ±10% in the steps of 1.5%.

In the PowerFactory simulation study the following steps are taken:

1) At the start of control cycle, the voltage profile in the A1 distribution network can be obtained from a PowerFactory simulation study when the load demand is set to the minimum value of 0.4kW for each house at each given level of PV power injection (starting from NO PV power injection).

2) If the voltage output at feeder end-bus is less than 0.89p.u, the transformer tap increased by sufficient steps to raise it over 0.89p.u. If the distribution feeder end-bus voltage is above 1.1p.u, the distribution transformer tap decreased to reduce it below 1.1p.u. If it is between 0.89 and 1.1p.u, the transformer tap is keep at its neutral tap position. The required tap position setting can be determined based on the real power injection, which was described in detailed in chapter 4.

3) The simulation study will be repeated for different levels of PV power injection.
5.2.2 The result presentation for the electronic tap changer

Figure 19 shows the effectiveness of the voltage regulation strategy that uses an electronic transformer tap changer in the A1 distribution network.

![Voltage profile of the A1 distribution network with minimum load demand using electronic tap changer](image)

Figure 19: The effectiveness of electronic transformer taps changing in A1 distribution network with increased PV generation
5.2.3 Discussion

Figure 20: The comparative voltage regulation performance of electronic tap changing and the base case

Figure 20 shows the voltage profile at feeder end bus 4 using the electronic tap changer as PV penetration increases, which compares the effect of tap changing to the base case. Specifically, it can be seen that, compared with the base case scenario, where the voltage at bus 4 is over the allowed limit when more than 2kW PV power injection from each house, the proposed method is able to maintain the voltage output within the regulatory limits even at maximum PV power injection(3.4kW) of each house.
6. Other voltage control strategies to manage the voltage rise issue caused by PV penetration

Chapter 6 will focus on local control methods for managing the voltage rise on the A1 distribution network. The PV inverters can be used for distributed network control. The potential exists for PV inverters are to manage the voltage profile of the distribution network by injecting (absorbing) the reactive power into the grid. Alternatively, voltage rise can be mitigated by reducing the active power output of the DG. These local control methods are called Reactive Power management (RPM) and Solar Power Curtailment (SPC) respectively.

6.1 Reactive Power Management (RPM)

6.1.1 Introduction

For residential rooftop PV panels, most inverters generally operate at unity power factor over their entire active power output range. In some case, a PV inverter does not provide any reactive power support while still operating at maximum PV power output. If one wishes to continue increasing the PV power injection, this will result in a voltage rise problem. However, there is an increasing recognition of the potential for PV inverters is to manage the voltage profile of distribution feeders by injecting (absorbing) reactive power into the grid at full PV power injection as shown in Figure 21.

![Figure 21: The reactive power capacity of PV inverter [19]](image-url)
The RPM strategy sets the reactive power injection from PV inverters according to a required relationship between the inverter power factor and the voltage output. One approach is to specify the required power factor according to the worst voltage at its highest voltage rise level and then to calculate the required reactive power injection as a function of the actual real power injection [3]. This algorithm for this voltage control strategy will be illustrated in detail in the following part.

6.1.2 The simulation study within PowerFactory

In order to investigate the RPM strategy, the following steps were taken:

Step 1: At the start of a control cycle, the voltage profile in the A1 distribution network can be calculated using PowerFactory simulation study when the load demand is set to the minimum value of 0.4kW for each house and each given level of PV power injection.

Step 2: Determine the required power factor according to the feeder end bus voltage

As mentioned in chapter 2.2.1, when the PV inverter operating at unity power factor with the maximum PV power output \( P_{\text{max}} \) and at maximum allowed voltage limits \( V_{\text{max}} \) at the feeder end-bus, the voltage change \( \Delta V_1 \) is given by

\[
\Delta V_1 = \frac{P_{\text{max}}R}{V_{\text{max}}}
\]

This will result in the voltage rise issue and the PV inverter will be over-rated as PV power output continues to increase. Figure 22 shows the voltage profile of the A1 distribution network for the worst case scenario (PV generation peaks while the load demand is at the lowest value). As a result the voltage rises at the highest level. It can be noted from Figure 22 that the highest voltage rise level is 1.178-1=0.178pu at feeder end bus 4. Therefore, the PV inverters with a 17.8% overrating can be used in this context so that the inverters can provide reactive power support in order to manage the voltage profile within the maximum allow voltage limits even at the maximum PV power generation.
When the PV inverter operates at unity power factor operates with fixed Maximum PV output with 17.8% overrating \((S_{\text{rated}} = 1.178p_{\max})\), the reactive power support must be increased from zero to at least 62.26% even at maximum PV power generation in order to maintain the feeder end-bus 4 voltage within the maximum allow voltage limits, as shown in Figure 23. This results in a power factor capability of unity to 0.848 leading or lagging. An overview of the power factor deviation will be providing in Appendix A. Therefore, the operation range of inverter from 0.848 lagging to 0.848 leading power will be used for this investigation.

![Figure 22: The highest voltage rise level in the A1 distribution network for the worst case scenario](image)

![Figure 23: The VAR power capacity of PV inverter at full PV power output [4]](image)
Step 3: Calculate the reactive power injection based on the PV power injection 17.8% over-rating extends the operation range of inverter from 0.848 lagging to 0.848 leading power factors, which was determined in the Step 2. The VAR injection from a PV inverter operating at 0.848 PF is about 52.8%, as shown in Figure 24.

![Figure 24](image)

Figure 24: The capability of VAR power support from PV inverter between 0.848 lagging and 0.848 leading [20].

The characteristic shown in Figure 24 (b) can be implemented using Equation (6) [20], which calculates the VAR power injection of each bus in the distribution network based on the PV power injection. These equations are implemented in Power Factory, so that the voltage with RPM can be achieved automatically. Table 6 summarizes the reactive power injection at each bus of the A1 distribution network as the PV power injection increases from PV panels.

\[
\frac{Q_{\text{ref}}}{P_{\text{max}}} = \begin{cases} 
10 \times \left( \frac{Q_{\theta}}{P_{\text{max}}} \right)_{\text{Max}} \times \left( -\frac{1}{V_{\text{rated}}} V_{\text{rms}} + 1 \right) & 0.9V_{\text{rated}} < V_{\text{rms}} < 1.1V_{\text{rated}} \\
\left( \frac{Q_{\theta}}{P_{\text{max}}} \right)_{\text{Max}} & V_{\text{rms}} \ll 0.9V_{\text{rated}} \\
-\left( \frac{Q_{\theta}}{P_{\text{max}}} \right)_{\text{Max}} & V_{\text{rms}} \gg 1.1V_{\text{rated}}
\end{cases}
\]  

(6)
Table 6: A summary of the calculated value of VAR injection at each bus of A1 distribution network

<table>
<thead>
<tr>
<th>Zone</th>
<th>No PV power injection (KVAR)</th>
<th>1 KW PV power injection (kVAR)</th>
<th>2 KW PV power injection (kVAR)</th>
<th>3KW PV power injection (kVAR)</th>
<th>Maximum PV power injection (3.4kW) (kVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone1 bus 1</td>
<td>0.196</td>
<td>-0.348</td>
<td>-1.584</td>
<td>-3.231</td>
<td>-3.976</td>
</tr>
<tr>
<td>Zone1 bus 2</td>
<td>4.039</td>
<td>-5.956</td>
<td>-30.154</td>
<td>-70.520</td>
<td>-90.595</td>
</tr>
<tr>
<td>Zone 1 bus 4</td>
<td>7.876</td>
<td>-11.532</td>
<td>-58.412</td>
<td>-95.040</td>
<td>-107.467</td>
</tr>
<tr>
<td>Zone 2 bus 1</td>
<td>0.222</td>
<td>-0.380</td>
<td>-1.580</td>
<td>-3.707</td>
<td>-4.514</td>
</tr>
<tr>
<td>Zone 2 bus 2</td>
<td>4.061</td>
<td>-5.988</td>
<td>-24.212</td>
<td>-70.900</td>
<td>-91.132</td>
</tr>
<tr>
<td>Zone 2 bus 3</td>
<td>6.621</td>
<td>-9.726</td>
<td>-43.240</td>
<td>-95.040</td>
<td>-107.467</td>
</tr>
<tr>
<td>Zone 2 bus 4</td>
<td>7.898</td>
<td>-11.563</td>
<td>-52.722</td>
<td>-95.040</td>
<td>-107.467</td>
</tr>
<tr>
<td>Zone 3 bus 1</td>
<td>0.241</td>
<td>-0.412</td>
<td>-1.896</td>
<td>-3.992</td>
<td>-4.943</td>
</tr>
<tr>
<td>Zone 3 bus 2</td>
<td>4.080</td>
<td>-6.019</td>
<td>-30.470</td>
<td>-71.280</td>
<td>-91.562</td>
</tr>
<tr>
<td>Zone 3 bus 3</td>
<td>6.640</td>
<td>-9.757</td>
<td>-49.308</td>
<td>-95.040</td>
<td>-107.467</td>
</tr>
<tr>
<td>Zone 3 bus 4</td>
<td>7.917</td>
<td>-11.595</td>
<td>-58.728</td>
<td>-95.040</td>
<td>-107.467</td>
</tr>
<tr>
<td>Zone 4 BUS 1</td>
<td>0.849</td>
<td>-1.394</td>
<td>-6.827</td>
<td>-15.682</td>
<td>-19.989</td>
</tr>
<tr>
<td>Zone 4 BUS 2</td>
<td>4.689</td>
<td>-6.970</td>
<td>-35.211</td>
<td>-82.305</td>
<td>-105.640</td>
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<tr>
<td>Zone 4 BUS 3</td>
<td>7.245</td>
<td>-10.676</td>
<td>-53.986</td>
<td>-95.040</td>
<td>-107.467</td>
</tr>
<tr>
<td>Zone 4 BUS 4</td>
<td>8.522</td>
<td>-12.545</td>
<td>-63.360</td>
<td>-95.040</td>
<td>-107.467</td>
</tr>
<tr>
<td>Zone 5 BUS 1</td>
<td>0</td>
<td>-1.394</td>
<td>-6.954</td>
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<td>-20.204</td>
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<td>Zone 5 BUS 2</td>
<td>3.827</td>
<td>-7.001</td>
<td>-35.275</td>
<td>-82.400</td>
<td>-105.855</td>
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<td>Zone 5 BUS 3</td>
<td>6.384</td>
<td>-10.708</td>
<td>-54.050</td>
<td>-95.040</td>
<td>-107.467</td>
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<td>Zone 5 BUS 4</td>
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<td>-12.545</td>
<td>-63.360</td>
<td>-95.040</td>
<td>-107.467</td>
</tr>
<tr>
<td>Zone 6 BUS 1</td>
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<td>-1.426</td>
<td>-7.017</td>
<td>-16.062</td>
<td>-20.419</td>
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<td>Zone 6 BUS 2</td>
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<td>-82.590</td>
<td>-106.070</td>
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<td>Zone 6 BUS 3</td>
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<td>-54.113</td>
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<td>Zone 6 BUS 4</td>
<td>8.541</td>
<td>-12.577</td>
<td>-63.360</td>
<td>-95.040</td>
<td>-107.467</td>
</tr>
</tbody>
</table>
6.1.3 The results presentation for the RPM strategy

Figure 25 shows the voltage profile of the A1 distribution network with increased PV power generation using the RPM strategy.

![Diagram showing voltage profile with increased PV generation](image)

Figure 25: The RPM strategy performance of the voltage profile in A1 distribution network with increased PV power injection from PV panels
6.1.4 Discussion

Figure 26 shows the voltage profile at feeder end bus 4 of zone 6 with and without using RPM strategy as the PV power injection increases.

![Figure 26: The comparative voltage regulation performance of the RPM and the base case (NO voltage regulation)](image)

It can be noted from Figure 26 that there is a sharp drop at feeder end-bus 4 after using the RPM strategy. The RPM strategy can maintain acceptable voltages along the LV distribution feeder, except for the maximum PV power injection (3.4kW from each house). This is probably because reactive power injection is not a particularly effective voltage regulatory strategy for the LV distribution feeders with a high resistive, and also the capacity of the PV inverter to inject VAR power is quite limited when the feeders is operating in the worst case scenario.
6.2 Solar Power Curtailment (SPC)

6.2.1 Introduction

The SPC can provide an alternative to reactive power injection when it comes to the voltage control strategies. The solar power output can be directly limited when the inverter voltage has reached the over-voltage level. It is mainly used for LV distribution networks with high resistive characteristics in transmission lines where the inverter voltage is more closely related to active PV power injection.

One approach is to use a predefined characteristic based on inverter voltage and output power, as shown in Figure 27. It can be clearly noted that when the voltage is approaching the maximum allowed value, the inverter is asked to stop working with MPPT, and then move instead to produce less power if the feeder continues to face an over-voltage problem.

---

![Figure 27: The real power curtailment of PV inverters [5]](image)

---

Another alternative is a power curtailment algorithm where the output power from a PV inverter is a function of inverter voltage, as given by Equation (7) [5]:

\[
P_{\text{inv}} = \begin{cases} 
P_{\text{MPPT}} & V \ll V_{\text{cri}} \\
P_{\text{MPPT}} - K_{\text{droop}}(V - V_{\text{cri}}) & V > V_{\text{cri}} \end{cases} \quad \ldots (7)
\]

where 
- \( P_{\text{inv}} \) = the output power of the inverter
- \( P_{\text{MPPT}} \) = the output power from MPPT
- \( V_{\text{inv}} \) = the inverter voltage
- \( V_{\text{cri}} \) = a critical voltage
- \( K_{\text{droop}} \) = the droop coefficient = \( \frac{P_{\text{max}}}{V_{\text{MAX}} - V_{\text{MIN}} - V_{\text{cri}}} \)
\[ V_{\text{MAX-cri}} = \text{the maximum allowed voltage} \]
\[ V_{\text{MIN-cri}} = \text{the minimum allowed voltage} \]

Specifically, when the voltage has not reached its critical value, the inverter is asked to work with MPPT and produce the maximum available output power. If the feeder reaches its over-voltage level, an inverter output power is defined based on the droop coefficient \((K_{\text{droop}})\) as shown in Equation 7.

6.2.2 The simulation study using PowerFactoy

In order to investigate the SPC strategy, the simulation study used the following steps:

Step 1: At the start of control cycle, the voltage profile in the A1 distribution network can be calculated using a PowerFactory, where the load demand is set to the minimum value of 0.4kW (per house) for each given level of PV power injection (from residential rooftop PV panels).

Step 2: The PV power output from the inverters working with MPPT can be calculated and implemented at each bus of the A1 distribution network within PowerFactory. Then, voltage profile with SPCS can be derived automatically. Table 7 summarizes the PV power output from PV inverters as the PV generation increases from PV panels.
Table 7: A summary of the PV power output from PV inverters as the PV generation increases.

<table>
<thead>
<tr>
<th>Zone</th>
<th>No PV power injection (KW)</th>
<th>1 KW PV power generation (KW)</th>
<th>2 KW PV power generation (KW)</th>
<th>3KW PV power generation (KW)</th>
<th>Maximum PV power generation (KW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1 bus 1</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>180</td>
<td>204</td>
</tr>
<tr>
<td>Zone 1 bus 2</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>180</td>
<td>204</td>
</tr>
<tr>
<td>Zone 1 bus 3</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>162.256</td>
<td>167.842</td>
</tr>
<tr>
<td>Zone 1 bus 4</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>142.455</td>
<td>142.375</td>
</tr>
<tr>
<td>Zone 2 bus 1</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>180</td>
<td>204</td>
</tr>
<tr>
<td>Zone 2 bus 2</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>180</td>
<td>204</td>
</tr>
<tr>
<td>Zone 2 bus 3</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>161.913</td>
<td>167.453</td>
</tr>
<tr>
<td>Zone 2 bus 4</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>142.112</td>
<td>141.986</td>
</tr>
<tr>
<td>Zone 3 bus 1</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>180</td>
<td>204</td>
</tr>
<tr>
<td>Zone 3 bus 2</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>180</td>
<td>204</td>
</tr>
<tr>
<td>Zone 3 bus 3</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>161.570</td>
<td>167.064</td>
</tr>
<tr>
<td>Zone 3 bus 4</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>141.855</td>
<td>141.598</td>
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<tr>
<td>Zone 4 bus 1</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>180</td>
<td>204</td>
</tr>
<tr>
<td>Zone 4 bus 2</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>180</td>
<td>204</td>
</tr>
<tr>
<td>Zone 4 bus 3</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>152.055</td>
<td>154.817</td>
</tr>
<tr>
<td>Zone 4 bus 4</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>132.425</td>
<td>129.545</td>
</tr>
<tr>
<td>Zone 5 bus 1</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>180</td>
<td>204</td>
</tr>
<tr>
<td>Zone 5 bus 2</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>180</td>
<td>204</td>
</tr>
<tr>
<td>Zone 5 bus 3</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>151.884</td>
<td>154.622</td>
</tr>
<tr>
<td>Zone 5 bus 4</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>132.254</td>
<td>129.448</td>
</tr>
<tr>
<td>Zone 6 bus 1</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>180</td>
<td>204</td>
</tr>
<tr>
<td>Zone 6 bus 2</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>180</td>
<td>204</td>
</tr>
<tr>
<td>Zone 6 bus 3</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>151.712</td>
<td>154.428</td>
</tr>
<tr>
<td>Zone 6 bus 4</td>
<td>0</td>
<td>60</td>
<td>120</td>
<td>132.168</td>
<td>129.253</td>
</tr>
</tbody>
</table>
6.2.3 The result presentation for the SPC strategy

Figure 28 shows the voltage profile of the A1 distribution network with the SPC strategy.

Figure 28: The voltage profile of the A1 distribution network with the SPC strategy
6.2.4 Discussion

Figure 29 shows the voltage profile at feeder end bus 4 of zone 6 with and without the SPC strategy as the function of increased PV power generation.

![The comparative voltage regulation performance of the SPC strategy and the base case (no voltage regulation)](image)

Figure 29: The comparative voltage regulation performance of the SPC strategy and the base case (NO voltage regulation)

It can be clearly noted that there is a sharp voltage drop at the feeder end bus voltage after using the SPC strategy. However, the SPC strategy cannot maintain the bus voltage profile within the regulatory limits when the PV power output increases to 2kW at each house. A significant over-voltage can still be observed based on the maximum allowable voltage. The results show the poor operational performance of MPPT for PV inverters in LV distribution feeders when it comes to managing the voltage rise issue. In addition, the aim of integrating the distributed renewable generation into the grid is to inject as much active power as possible rather than limiting it. This issue will not be discussed in detail in this project, but may be the subject of studies in the future.

Therefore, the SPC does not provide an effective voltage control strategy for the A1 distribution network.
7. A further investigation into voltage control strategies

7.1 Some drawbacks among voltage control methods

The strategy for power electronic tap changing presented in chapter 4 and the integrated strategies presented in chapter 6 have been investigated as the PV generation level increases, which provide different levels of performance on voltage rise mitigation of the A1 distribution network. However, the optimal voltage profile in the A1 distribution network still cannot be achieved by a coordination of these voltage control strategies alone. This performance is worse when the network is subject to the worst case scenario of maximum PV power output peaks in the residential areas with the minimum load demand.

7.1.1 The electronic tap changer performance

Figure 30 shows the voltage profile characteristic at zone 6 with the coordination of an electronic transformer tap changer, which is compared to the base case scenario (NO voltage control regulation). It can be clearly noted that the entire voltage profile is operating within the regulatory limit even for the worst case scenario. However, this voltage regulation affects each of the bus voltages along the LV distribution feeder, even in parts of the feeder that do not have a voltage problem. In order to keep the worst voltage within the limits, some buses near the distribution substation incur a large voltage drop. For example, the voltage profile from the distribution transformer to the house cluster of bus 1 is operating within the voltage range, but the voltage decreased by a tap changing below 0.95pu, as shown in Figure 30.
7.1.2 The RPM strategy performance

It can be noted from Figure 31 that the RPM strategy is not able to maintain the feeder end-bus voltage within the required limits under the worst case scenario, although some voltage rise mitigation can be achieved through the RPM strategy.
As expected, the optimal voltage profile regulation is not only to keep the entire voltage profile of distribution feeders within the regulatory limit but also to make a uniform voltage profile along the feeders. This can be achieved by a combined voltage control strategy that includes RPS and electronic tap changing.

### 7.2 The Combined Voltage Control Strategy

The combined voltage control strategy is to implement the RPM strategy at each bus of the A1 distribution network with each given level of PV generation, and then to coordinate each distribution zone with the electronic transformer tap changing.

#### 7.2.1 The simulation study using PowerFactory

The simulation study in PowerFactory used the following steps:

Step 1: The voltage profile of the A1 distribution network can be calculated using PowerFactory with the minimum load demand (0.4kW) at each house for a given level of PV generation (Starting from 1kW power injection from residential rooftop PV panels).

Step 2: The RPM strategy is then implemented in the A1 distribution network model, which is based on the approach presenting in chapter 6.1.

Step 3: If the end bus voltage is still above 1.1pu, the transformer tap is decreased by sufficient steps to lower it below 1.1pu.

Step 4: The simulation study is repeated as the given PV generation increases to the maximum power output (3.4kW) per house.
7.2.2 The result presentation for the combined voltage strategy

Figure 32 shows the voltage profile of the A1 distribution network with the combined strategy.

![Figure 32: The effectiveness of the combined voltage control strategy in the A1 distribution network](image-url)
7.2.3 Discussion

Figure 33 shows the voltage profile at the last zone for the worst case scenario with different strategies.

Figure 33: The performance of voltage profile at the end distribution feeder zone with different control strategies

It can be noted that the strategies of the base case (no voltage regulation) and the RPM are not able to maintain the entire feeder bus voltage within the regulatory limits when the network is subject to the worst case scenario, while the combined strategy and the power electronic tap changer have a better voltage control performance that the worst voltage (1.1pu) is still within the allowed range as shown in Figure 33. Also, it can be clearly noted that a more uniform voltage profile along the LV feeder is achieved by the combined strategy compared to using the power electronic tap changing alone.
8. Conclusion

8.1 The conclusion of the thesis

This thesis explores the voltage regulation performance of a new electronic tap changing for a distribution transformer in order to mitigate the voltage rise problem in the A1 distribution network for increasing levels of PV generation. Voltage fluctuation issues on the A1 distribution network with increased PV generation were investigated. Then, various voltage control strategies were implemented in the system in order to confirm their voltage control performance. The investigations were supported by using the PowerFactory simulation software, version 15.2.

Chapter 2 reviewed the solar energy resource energy and rooftop PV installation in Australia, and showed some bad effects on the voltage profile of distribution networks with high PV generation. Various PV penetration levels and load consumption results in two worst case scenarios like voltage rise and voltage fluctuation. The approach to the modeling of the A1 distribution network within PowerFactory was discussed in chapter 3, and the voltage control method for a coordination of power electronic transformer tap changing was described in chapter 4.

The results of the thesis presented in chapter 5. It was observed that voltages along the distribution network increase as the PV generation increases. It was found that voltage rise mitigation can be achieved through coordination of an electronic tap changer at the distribution transformer. All the voltage levels along the A1 distribution network remain within the regulatory limits.

In chapter 6, the voltage control strategies for RPM and SPC were described. It was noted that the coordinated RPM of the grid-connected PV inverter can maintain the voltage profile within the permitted range except when the network is subject to the worst case scenario. In addition, the SPC strategy does not provide an effective voltage control strategy for the A1 distribution network, because it is not able to maintain all the voltage within the limits for PV outputs above 3kW from each house, as shown in Table 8.

In chapter 7, a combined voltage control strategy of RPM plus electronic tap changing was implemented in the A1 distribution network, and it was compared to the base case scenario (no voltage regulation), the RPM strategy and electronic tap changer. The combined strategy
achieved the optimal voltage profile of the network. The results are summarized in Table 8.

Table 8: A summary of the voltage profile at end feeder bus 4 (the worst voltage) with minimum load demand

<table>
<thead>
<tr>
<th>Control Strategies</th>
<th>Scenarios</th>
<th>Case Voltage Output (pu)</th>
<th>1kW PV injection per house</th>
<th>2kW PV injection per house</th>
<th>3kW PV injection per house</th>
<th>Maximum PV injection(3.4kW) per house</th>
</tr>
</thead>
<tbody>
<tr>
<td>The base case (NO voltage regulation)</td>
<td></td>
<td></td>
<td>1.04</td>
<td>1.1</td>
<td>1.156</td>
<td>1.178</td>
</tr>
<tr>
<td>The implement of electronic tap changing</td>
<td></td>
<td></td>
<td>1.04</td>
<td>1.1</td>
<td>1.1</td>
<td>1.095</td>
</tr>
<tr>
<td>The RPM strategy</td>
<td></td>
<td></td>
<td>1.034</td>
<td>1.082</td>
<td>1.1</td>
<td>1.122</td>
</tr>
<tr>
<td>The SPC strategy</td>
<td></td>
<td></td>
<td>1.04</td>
<td>1.1</td>
<td>1.125</td>
<td>1.129</td>
</tr>
<tr>
<td>The combined strategy</td>
<td></td>
<td></td>
<td>1.034</td>
<td>1.082</td>
<td>1.098</td>
<td>1.1</td>
</tr>
</tbody>
</table>

8.2 Scope for future work

8.2.1 Power loss issue
High PV power injection can change the direction of power flow in the LV distribution feeders with high resistive of transmission line, which results in a high power loss. Therefore, further research may focus on different strategies corresponding to the LV feeder loss.

8.2.2 Optimizing the active power output
Future research could investigate how the voltage profile can still be maintained within the accepted limits when the maximum output could be optimized and the research could investigate the distributed PV system under current generating conditions, rather than its initial commissioning conditions and limitations.
8.2.3 Transient investigation on voltage regulation of distribution networks

Steady-state investigation was implemented on the thesis while the transient behaviors of the distribution network with increased PV generation need to be done in the future work. For example as the PV generation on such a system gets higher, the fault current profile on a system will be considerably different than that of the feeder without PV generation [21]. Further investigation may be focus on the fault current on a distribution network with high PV generation.
References


7. P. Lu, “An investigation into voltage control approaches on an example distribution feeder to increase PV penetration”, Perth, Western Australia: Murdoch University, June 2015.


15. J. Faiz, B. Siahkolah, “Differences between Conventional and Electronic Tap-Changers
and Modifications of Controller”, IEEE TRANSACTIONS ON POWER DELIVERY, JULY 2006
18. Electrical4u, “Switching or ON-OFF Characteristics of SCR”, Online Electrical Engineering,
19. Reactive Power Capability, Western Electricity Coordinating Council, August 2010
Appendix

Appendix A:
At the beginning, the PV inverter operates at PF=1
With this 17.8% increase in the inverter size
\[
S_{\text{rated}}^g = 1.178 P_{\text{max}}^g
\]

In order to keep the end bus voltage within the maximum allow voltage limits, the reactive power injection needs to be:
\[
Q_{\text{min}} = \sqrt{(S_{\text{rated}}^g)^2 - (P_{\text{max}}^g)^2} = \sqrt{(1.178 P_{\text{max}}^g)^2 - (P_{\text{max}}^g)^2} = |0.6226 P_{\text{max}}^g| 
\]

Then, the PV inverter operates at 0.848 leading or lagging power with the reactive power injection even at the maximum PV power generation.
\[
P_F = \frac{P_{\text{max}}^g}{S_{\text{rated}}^g} = \frac{P_{\text{max}}^g}{1.178 P_{\text{max}}^g} = 0.848 \text{ lagging or leading power}
\]

The VAR power injection at 0.848 power factor is \(0.848 \times |0.6226 P_{\text{max}}^g| = |0.528 P_{\text{max}}^g|\)
Appendix B: Model Parameter used in PowerFactory

1. Transformer model

1.1 HV substation transformer

<table>
<thead>
<tr>
<th>Name</th>
<th>The 132/22kV 2-winding Transformer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>Three Phase Transformer</td>
</tr>
<tr>
<td>Rated Power</td>
<td>20MVA</td>
</tr>
<tr>
<td>Nominal Frequency</td>
<td>50HZ</td>
</tr>
<tr>
<td>Rated Voltage for HV-side</td>
<td>132kV</td>
</tr>
<tr>
<td>Vector Group for HV-side</td>
<td>Delta</td>
</tr>
<tr>
<td>Rated Voltage for LV-side</td>
<td>22kV</td>
</tr>
<tr>
<td>Vector Group for LV-side</td>
<td>Delta</td>
</tr>
<tr>
<td>Short-Circuit voltage</td>
<td>6%</td>
</tr>
<tr>
<td>Copper Losses</td>
<td>0kW</td>
</tr>
</tbody>
</table>

1.2 LV distribution transformer

<table>
<thead>
<tr>
<th>Name</th>
<th>The 22/0.4kV 2-winding Transformer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>Three Phase Transformer</td>
</tr>
<tr>
<td>Rated Power</td>
<td>0.63MVA</td>
</tr>
<tr>
<td>Nominal Frequency</td>
<td>50HZ</td>
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<tr>
<td>Rated Voltage for HV-side</td>
<td>22kV</td>
</tr>
<tr>
<td>Vector Group for HV-side</td>
<td>Delta</td>
</tr>
<tr>
<td>Rated Voltage for LV-side</td>
<td>0.4kV</td>
</tr>
<tr>
<td>Vector Group for LV-side</td>
<td>YN</td>
</tr>
<tr>
<td>Short-Circuit voltage</td>
<td>3%</td>
</tr>
<tr>
<td>Copper Losses</td>
<td>3kW</td>
</tr>
</tbody>
</table>
2. Cable line model

2.1 LV cable

<table>
<thead>
<tr>
<th>Name</th>
<th>400V Transmission line: Cable data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>400V</td>
</tr>
<tr>
<td>Nominal Frequency</td>
<td>50HZ</td>
</tr>
<tr>
<td>System Type</td>
<td>AC</td>
</tr>
<tr>
<td>Conductor material</td>
<td>Copper</td>
</tr>
<tr>
<td>AC-Resistance R</td>
<td>0.270Ohm/km</td>
</tr>
<tr>
<td>Reactance X’</td>
<td>0.0735Ohm/km</td>
</tr>
</tbody>
</table>

2.1 HV cable

<table>
<thead>
<tr>
<th>Name</th>
<th>22KV Transmission line: Cable data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>22kV</td>
</tr>
<tr>
<td>Nominal Frequency</td>
<td>50HZ</td>
</tr>
<tr>
<td>System Type</td>
<td>AC</td>
</tr>
<tr>
<td>Conductor material</td>
<td>Copper</td>
</tr>
<tr>
<td>AC-Resistance R</td>
<td>0.161Ohm/km</td>
</tr>
<tr>
<td>Reactance X’</td>
<td>0.0670Ohm/km</td>
</tr>
</tbody>
</table>
The end