Simulation Modelling of Microgrids with Photovoltaic Renewable Energy Sources using PSCAD

Ashley Rossiter

The University of New South Wales at the Australian Defence Force Academy

Studies into microgrid stability and control schemes by industry engineers and academics require accurate simulation modelling in electromagnetic transient (EMT) environments. PSCAD, an EMT software package provides a suitable platform for conducting AC and DC power system studies but necessitates development of detailed and complex models. This paper presents the development, testing and validation of two microgrid models using PSCAD to assist current research into PV RES microgrid control schemes. The development of these models minimizes the in-depth software training required to design and implement relevant models using PSCAD. The first model provides a platform to investigate voltage control interactions at the point of common coupling (PCC) within a grid connected microgrid. The second model was developed to provide a model of islanded operation power sharing with master/slave communication control. This paper provides details of the model development and implementation for both relevant research scenarios. Using relevant simulations each model was tested for baseline function and control stability. Model steady-state stability validation was confirmed using Gauss-Seidel load-flow analytical calculations.

Contents
I. Introduction 2
II. Project Scope 3
III. Aims 3
IV. Background 3
A. Microgrid 3
B. Simulation Software 3
C. PV Inverter and control Systems 3
V. Model Implementation 4
A. PSCAD PV RES Model 4
B. Grid Connected Microgrid Network Model 5
C. Islanded Microgrid Network Model 7
VI. Conclusion 9
VII. Recommendations 9
References 11

Nomenclature
DG = Distribution Generation       VSIs = Voltage source inverters
PV = Photovoltaic                 MPPT = Maximum power point tracking
RESs = Renewable Generation Sources RMS = Root Mean Square
DERs = Distribution energy resources PI = Proportional Integral
PECs = Power electronic converters P = Active Power
MG = Microgrid                    Q = Reactive Power
B/ESS = Battery/Energy storage system \( V_{rms} \) = RMS Voltage
PCC = Point of common coupling \( \delta \) = Delta (Phase angle)
EMT = Electromagnetic transient AEMO = Australian Energy Market Operator
SUT = System under test

1 PLTOFF, School of Engineering & Information Technology. ZEIT4500/4501
I. Introduction

The world’s power systems have undergone a major transformation over the past several decades. The reliance on traditional thermal based power production using fossil fuels is slowly reducing due to aging technologies and carbon emission reduction targets. To face the challenges of increasing power demand and decrease in large transmission supply many power systems are shifting to distribution generation (DG) resources [3]. Renewable generation sources (RESs), mainly Photovoltaic (PV) and wind are the primary distribution energy resources (DERs) [4, 5]. PV RES systems have grown dramatically over the past decade, particularly small-scale PV systems (domestic roof-top mounted installations). For example, in Australia the Clean Energy Regulator recorded 1,054,156 installations as of June 2013\(^2\) to over 2,958,255 in March 2018\(^3\).

The increasing penetration of PV and other RESs into conventional DG networks connected through power electronic converters (PECs) poses system operators both challenges and opportunities in system stability and control. One method being implemented to help manage and deploy RESs throughout electrical systems is through microgrids [6]. Microgrids allow the autonomous operation and control of a subset network of DERs, loads and energy storage system (ESS) that can be operated in both grid-connected and islanded modes [7-9]. The advantages of using microgrids is that they can be implemented within DG networks with minimal infrastructure changes, independently operate in the event of main network power disturbances and faults and seen as a single controllable subsystem to the main network [6]. Microgrid autonomous operation requires the control of each RES voltage regulation, frequency regulation and power flow to ensure the system is balanced with all load and connection modes. Complex control schemes are required to maintain stability which leads to several technical issues in that have been the focus in research papers such as; steady state and transient over/under voltage at point of common coupling (PCC), power quality, communication and protection systems [6, 7, 10]. Along with these issues, research into various DG control strategies have been detailed in [7], in particular communication-based master/slave and communication-less based signal injection for power sharing control.

Research, development and deployment of microgrids require advanced modelling to ensure control structure, fault protection measures and safety requirements are met. A common theme throughout the related literature demonstrates the need for accurate modelling and simulation of PECs using electromagnetic transient (EMT) software tools [11-15]. EMT simulation software modelling and analysis are also becoming mandatory requirements from energy regulatory bodies to ensure the system under test (SUT) meets all requirements prior to deployment. The Australian Energy Market Operator (AEMO) have released Power Systems Model Guide lines stating the model requirements for PECs [16]. For EMT simulations the AEMO have appointed PSCAD™/EMTDC™ (PSCAD) as the EMT simulation software package [16].

PSCAD, an advanced industry standard software tool, provides academics, researchers and power industry experts with an appropriate platform to develop and test power systems in the EMT environment. PSCAD provides users with a comprehensive component library and analysis tools to create the required scenario-based models. PSCAD models are very comprehensive and built from first principle requiring significant experience in the software package and the SUT.

The aim of this project was to develop flexible but comprehensive simulation models using PSCAD in order to conduct EMT studies into two microgrid network configurations comprised of PV RESs. The two models are based upon two scenarios currently being researched at UNSW. The first is grid-connected MG voltage oscillations caused by multiple PV controllers interacting at the PCC and the second is power sharing in islanded microgrids. From this, the software learning overhead and model development required will be minimized for researchers using these models. This research will add to an increasing body of research on microgrid control systems in grid-connected and island modes being conducted at UNSW.

The following sections are detailed as follows; section two and three detail the scope and aim of the project, section four provides background into information about microgrids, PSCAD modelling software and PV RESs control schemes, section five describes model development, testing and validation and sections six and seven detail the conclusions of this project and future direction for further model development.

\(^2\) Total PV installation and system size data from Clean Energy Regulator, current as of June 2013.

\(^3\) Total PV installation and system size data from Clean Energy Regulator, current as of March 2018; http://www.cleanenergyregulator.gov.au/Infohub/Media-Centre/Pages/Resources/RET%20media%20resources/Small-scale-renewable-energy-tracker---Quarter-1-2018.aspx
II. Project Scope

This project involved the development and compilation of model platforms to allow studies into MGs comprised of PV generating sources. PV models developed for this project were based upon several PSCAD pre-built components and models that comprised of the following modules, PV array, DC-DC converter, three-phase voltage source inverters (VSIs), BESS, relevant component control mechanisms and result outputs. The DC-DC converter utilizes maximum power point tracking (MPPT) controller.

III. Aims

The aims of this project were to develop flexible but comprehensive simulation models using PSCAD in order to conduct EMT studies into two microgrid network configurations comprised of solar photovoltaic PV RESs. The first model focuses on grid-connected MG to investigate PCC voltage regulation control interactions and the second model is an extension of a UNSW research project into power sharing of an islanded MG with no synchronous generators connected.

IV. Background

A. Microgrids

Microgrids are defined as low-voltage power grid connecting distribution generation sources (typically RESs), loads and ESS and are capable of being operated autonomously in both grid-connected and islanded modes [6, 7, 17]. Microgrids assist in overcoming the stability and control issues faced by high level penetration of RESs into DG networks. The advantages of using MGs come at a cost of control complexity, as they require hierarchical level control of RESs operating in the microgrid. [7] states the main control aims of microgrids is to manage voltage and frequency regulation, load sharing, power flow and protection measures to name a few. It also goes on to provide a summary of the control level requirements, operating modes, and microgrid communications-based control to achieve these aims. The three levels of control voltage control, primary control and tertiary control where the models developed in this project focus on voltage and primary control. These levels are again detailed in [7] with grid-connected models focusing on voltage control and islanded focusing on primary control with communication.

B. Simulation Software

PSCAD is an industry standard power system software tool that provides accurate and comprehensive methods of simulating and testing power systems. The complex nature and the different elements contained within the power system requires comprehensive modeling in the EMT environment [15]. PSCADs EMT environment allows the full model representation of three-phase electricity networks consisting of transmission, distribution and generating sources including fast switching type devices such as VSIs used in RESs [18]. Other software packages such as PSS®E and Power Factory – DigSilent carryout simulation modelling such as Root Mean Square (RMS) and load flow analysis through phasor domain steady-state differential equations to calculate electrical circuits, capturing slower electromechanical transients. EMT simulations use time domain instantaneous value solutions to perform analysis of fast controls in power electronics, electrical devices, transients and temporary over-voltages, system strength (synchronous to non-synchronous generation), unbalanced faults and active/reactive power response of PECs through full operation conditions (fault/recovery), and low-high harmonics issues as described in [19]. PSCAD allows users to build advanced power systems using comprehensive library of models ranging from passive elements and control functions to complete electric systems ranging from full network such as South Australia’s power grid to simple battery modeling. Developed models can be easily simulated using powerful EMTDC simulation engine [13].

Power system operators such as South Australia (SA) under the AEMO are viewing EMT simulation modelling as a major requirement as non-synchronous generating sources increase throughout their grids. Following a 2016 blackout event where the entire SA network failed, AEMO carried out complete EMT modelling of the network using PSCAD, replicating events and scenarios that were similar to the 2016 blackout.

C. PV Inverter and control Systems

The inverter provides the interface between the PV generation unit and the external grid. Given the high penetration of inverter interfaced PV RESs their importance to power system stability and voltage control is fast being realised [5, 20-23]. The capabilities of power inverters used in PV systems provide PCC voltage control through reactive power injection/absorption [20]. Throughout the power system loads, generating sources, transmission lines and transformers introduce reactive power flow and cause the grid power factor to shift. This requires compensation through capacitor bank or inductor banks to be switched in to ensure system power factor. Through voltage control PV systems can contribute to power factor compensation and PCC voltage control by
changing the reactive power measures. As in the case of [24], the theory of instantaneous reactive power (PQ theory) which controls the active and reactive power output of the inverter is utilized in the PV model developed the current project. The voltage controller uses the input DC voltage to the inverter and reactive power measured at the output as the inputs to the controller. The inverter controller provides the appropriate reactive power by shifting the phase (power factor) between the voltage and current, and by doing so provides the reactive power compensation so the PCC voltage can be controlled appropriately (Figure 1). This figure shows how the PCC voltage in per unit scale varies in power factor, meaning either reactive power is being injected or absorbed. Primarily, PV systems inject reactive power.

The following sections provides a basic description of the system components and measuring methods important to model and simulation knowledge.

1. Proportional Integral (PI) Controllers

The PV model developed for this project uses PI controllers within the inverter P and Q controller and the MPPT controller for PV array and DC-DC converter. PI controllers are commonly used throughout the power industry, the main advantage of PI controllers is that the steady-state error is forced to zero. The main disadvantage of using this controller is response time of the system which can potentially cause issues relating to steady-state constraints as described in [25].

V. Model Implementation

This section details the development, testing and validation of the two model platforms completed for this project. Firstly, the PV RES model which is central to both network models is explained. The next two parts explain the grid-connected and islanded MG networks focusing on the scenario on which they are based and how it was implemented. Simulation results demonstrating MG network functions and model steady state analytical validation using Gauss-Seidel load flow analysis [26] are also presented.

A. PSCAD PV Model

The PV plant model was developed based on PSCAD developers, the Manitoba HVDC Research Centre generic models. Each PV model has an output rating of 0.1 – 0.3MW (dependent on PV array settings) and 460V connected through transformers to MG. A two stage PV plant model was selected and comprised of three modules and affiliated control networks; solar photovoltaic array, DC-DC boost converter and three-phase VSI, shown in Figure 2. This configuration was selected due to the additional control design flexibility and DC stability provided by the DC-DC boost converter as presented in [27]. A general description of the PV plant system and function of each module and affiliated control network will be explained in greater detail in the following sub-sections.

![Figure 2. Two stage PV plant model created using PSCAD](image-url)
1. **PV Array**

This model uses the standard photovoltaic module block which represents a solar cell and uses two inputs, irradiance and temperature and generates electricity through photovoltaic effect. The PV array model has several parameters to control the output of the array. The various parameters that can be modified include the array structure (no. of panels – series/parallel), cell properties and reference irradiation and temperature levels. The PV RES output power is set using these parameters. These parameter settings were provided by PSCAD support documentation for the required power output.

The PV array model output can be controlled using the irradiance and temperature scales, shown in Figure 2. This can be used to simulate varying environmental conditions such as cloud shadowing and daily temperature variations. For this simulation the primary focus is on PCC control and these settings are set for the relative simulation.

2. **DC-DC Boost Converter**

The PV array assembly is connected to a DC-DC boost converter. The DC-DC converter controls the voltage on the DC side of the PV plant through maximum power point tracking (MPPT) control. As the cell temperature and irradiation intensity changes, the ideal I-V characteristics for the solar cell changes (see Figure 3). The MPPT controller determines the maximum power output from this curve and sets the MMP reference voltage.

The DC-DC converter controller, shown in Figure 2 receives the MMP reference voltage and the actual voltage Vpv. The controller determines reference power signal which is that used to set the pulse width modulation (PWM) signal to control the insulated-gate bipolar transistor (IGBT) switch. Modifying the duty cycle of the IGBT switch, causes the charging and discharging process of the inductor and capacitor to change Vpv to track the reference MPP voltage.

3. **Three Phase Inverter**

The VSI stage converts the DC output of the DC-DC boost converter to three phase AC for connection to the grid. The power electronic circuit of the VSI comprised of 6 IGBT switches connected via DC link capacitor from the DC-DC boost converter and connect to the output through an LCL filter. The VCI control scheme is based on voltage and current control loops utilizing dq0 transformation reference frame which is described in detail in [7] and [22]. The real and reactive currents I_d and I_q along with V_out and Q are utilized through PI converters to control the DC voltage regulator and reactive power controller. The combination of these controllers provides the PWM reference signals to the 6 IGBT pulse firing generators.

**B. Grid Connected Microgrid Network Model**

1. **Model Scenario**

The issues focused in this model relate to grid over voltages resulting in curtailment or disconnections and voltage oscillations caused by multiple PV controllers interacting at the point of common connection (PCC). For power to flow the voltage of the supply bus needs to be higher than the receiving bus, i.e. DER to grid [12]. This can become a problem during periods of high level of active power injection by PV RESs or low-load situations [11]. Both these scenarios can lead to PCC voltage levels reaching critical levels resulting in the inverter curtailing power or disconnecting altogether. When multiple voltage control inverters are connected to PCC and each controller maintains PCC voltage levels, interaction between each system can cause the voltage at the PCC to oscillate leading to unstable operation. Both of these local control issues tend to be a result of controller parameters not being appropriately tuned to the structure of the grid [11]. The network configuration is based on a new PV system (PV3) being connected into an existing network containing two PV RESs. PV1 and PV2 controller parameters are fixed and was stable prior to new PV3 inclusion. The inclusion of PV3 into the network resulted in voltage control interactions at PCC.

2. **MG Network Model Setup**

The MG network developed for this project is comprised of a five bus network and contains three sections; an infinite bus representing the main grid, three buses connecting PV RESs and a central MG PCC bus connecting the PV RESs and load (0.6MW/Ph) to the grid (Figure 4). This model is a general representation of a MG with
the main grid supplied by the infinite source/sink capacity bus of 115kV down to intermediate voltage of 6.6kV through a wye-wye transformer and connected to PCC via a grid-tie circuit breaker and transmission line, T22. The PCC also known as the MG bus is weakly coupled to the grid through the transmission line and transformer so that the high-voltage bus and grid does not influence the voltage of PCC bus, imitating a weak network.

All RESs (PV generating units) are connected to the PCC bus via low-voltage transmission lines. PV units 1 – 3 are connected to all inverters providing voltage control of the PCC. To provide a variation to the MG network and demonstrate PCC bus voltage control by the two inverters a standard P load is connected via a timed breaker logic that disconnects and connects the load at set time to provide the system disturbance. For system control and monitoring multimeters are placed to measure each bus P, Q, Vrms, current, phase and frequency. These signals can be used by relevant controllers and/or sent to output channels for data observation and recording.

3. Model Testing and Validation

The combination of the grid-tied MG network shown in Figure 4 and the PV units were tested to ensure no compilation errors and that the system was stable. This was to ensure the model was configured correctly and all PV units PCC voltage control was confirmed to be within industry standards. Model steady state validation was carried by simulating the model for 30s and monitoring the P, Q, Vrms and phase of all five buses with each PV RESs voltage control set to 1pu. This data was compared with Gauss-Seidel load flow analysis calculations shown in table 1 and confirms modal baseline performance.

The model was tested through voltage step inputs at the PV voltage controllers and load disturbances injected at various times to demonstrate the model’s performance and response. The test was carried out for 90s with a step input applied to PV voltage controller at 10s intervals ranging from 0.95pu to 1.05pu and returning to 1.0pu. At 50s the 0.6MW load was disconnected and reconnected at 60s. At 85s the three PV systems were disconnected from the PCC. The results for the simulation are presented in Figure 5 and Figure 6. Figure 5 presents the bus voltage profiles and Figure 6 presents the active and reactive power profiles for PCC bus and PV1. From the results, each PV controller tracked the commanded input by varying the reactive power as described in section 4C.
increasing and decreasing the PCC voltage. Observation of controller interaction can be observed at load reconnection shown in plot insert at time 60s. The frequency of the oscillation was approx. 1.13Hz. The PI controller parameters of PV 1 and PV 2 were set to the same value, \( k_p = 0.1 \) and \( k_i = 0.01 \) and PV 3 set to \( k_p = 0.1 \) and \( k_i = 1.0 \) to replicate different installation described in the scenario. This variation can be seen in different response times at load reconnection, referring to purple and superimposed red/yellow plots in Figure 5.

The power profile presented in Figure 6 demonstrates how the active power output of PV 1 remains consistent through step changes but the reactive power injection and absorption follows as required. The power profiles for PV 2 and PV 3 were omitted as they responded in similar behavior to PV 1.

The results of the simulation demonstrate the ability of the model to respond to load disturbances and controller interactions laying the foundation for future research.

C. Islanded Microgrid Network Model

1. Model Scenario

Research projects into microgrid operation during islanded mode is currently a key focus at UNSW requiring various software-based models to perform simulations relating to development of control schemes. As previously explained EMT simulations are essential in capturing the critical behavior of MG networks involving RESs. This
model was developed to support current projects that are using DlgSilent simulation software models researching power sharing of RESs during islanded operation with no synchronous generating source.

2. **MG Network Model Setup**

The MG network was based on a 22kV four-bus system with an ideal source performing the master role providing frequency and voltage reference, shown in Figure 7. A PV with BESS and PV (slave sources) is connected to buses 2 and 3 respectively and provide the main MG DG energy source. Bus four is the PCC with the required metering and variable load bus used for simulations. The ideal source (represent a BESS VSI interface system) performs artificial droop control by balancing the system for all load conditions and communicating the required power of the slave RESs. To achieve power sharing each PV model required deloading, a control of active power output of DC-DC converters by replacing the MPPT input to the PWM controller with differential error signal from the ideal source meters (Communication based). The MPPT tracking is still used as $P_{\text{max}}$ limit as this is the maximum power capacity of the PV RES unit. Once the load disturbance is met by the ideal source, the master commands the slave energy sources to change their output until the power flow from/to the ideal source is zero. Relating to real world scenario, the BESS system would supply power as required and return to zero or charging state so that it doesn’t fully discharge.

3. **Model Testing and Validation**

The model was compiled and tested as per the previous network. Model steady state validation was carried out by simulating the model for 30s and monitoring the $P$, $Q$, $V_{\text{rms}}$, and phase of all four buses with a fixed load of 0.5MW. The two RESs was controlled to maintain output sharing of load and ideal source with zero output. This data was compared with Gauss-Seidel load flow analysis calculations shown in table 2 and confirms baseline performance.

![Figure 7. 4-Bus 22kV Islanded Microgrid with PV, PV-BESS RESs, load and Ideal source (BESS system) connected to PCC.](image)

<table>
<thead>
<tr>
<th>Bus Information</th>
<th>PSCAD Data</th>
<th>Load Flow Cales</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus #</td>
<td>Name</td>
<td>Type</td>
</tr>
<tr>
<td>BUS 1</td>
<td>Grid</td>
<td>Slack</td>
</tr>
<tr>
<td>BUS 2</td>
<td>PV1BESS</td>
<td>PQ</td>
</tr>
<tr>
<td>BUS 3</td>
<td>PV2</td>
<td>PQ</td>
</tr>
<tr>
<td>BUS 5</td>
<td>load (PCC)</td>
<td>PQ</td>
</tr>
</tbody>
</table>

Table 2: 4-Bus Islanded MG PSCAD steady-state simulation and load flow validation calculations
Model simulation testing was performed to verify the power sharing and downloading control of the two RESs under varying loads. A 50s simulation was performed with different load conditions switched on and off at set intervals. The results of this simulation are presented in Figure 8. Each PV RES had a minimum output power of 0.1MW before full disconnection is required therefore a constant 0.3MW load was connected for the duration of the test. At 10s an additional 0.100MW load was added and disconnected at 20s. At connection of load the BESS bus responded to balance the network, immediately the PV RESs responded returning the output of BESS source back to zero. This was repeated at 30s with a 0.05MW load. At 35s the PV2 PV array settings were changed to check for P\text{max limits of the MPPT control. Initially the BESS responded until PV1BESS was able to take the slack. The requirements for this model to provide network balance and power sharing through master/slave based communication and deloading control was achieved and confirmed through simulation.

### VI. Conclusion

The aim of this project was to assist current research into MG control by developing two flexible but comprehensive simulation models using PSCAD. The two models were based upon two scenarios which are currently being researched at UNSW. The first model was designed to investigate grid-connected MG voltage oscillations caused by multiple PV controllers interacting at the PCC. The second model was designed for power sharing in islanded microgrids simulations. To accurately analyze PECs control performance, modelling and simulations are required to be carried out using an EMT software environment such as PSCAD. Using PSCADs extensive pre-built sub-models, component libraries and detailed controllers built from first principles, comprehensive models can be created to represent systems ranging from simple plants through to whole electrical networks.

The models were implemented firstly by designing and compiling a two stage PV RES model comprised of a PV array, DC-DC boost converter controlled through MPPT and VSI using nested voltage and current control scheme in the dq0 reference frame. A grid connected 5-bus MG was implemented using three PV RES models and a fixed load to explore voltage control interactions at PCC. The implemented model demonstrated the PV voltage control capabilities of the PCC to voltage step inputs and provides an example of controller interactions causing small oscillations. A 4-bus autonomously controlled islanded MG was developed implementing two PV RES models, one with additional BESS system and an ideal source (master controller) connected to a load bus. The active power deloading control and power sharing capabilities were confirmed through simulation. The steady-state stability of the both grid connected and islanded models was validated using Gauss-Seidel load flow analysis.

As the penetration of RESs into DG networks increases, grid stability and control issues are likely to become increasingly problematic. Through implantation of microgrid technology these growing issues will become simpler for grid operators to manage. To ensure this remains true, research into MG control schemes will need to continue and grow as new technologies and theories emerge. These will require accurate simulation and modelling using software packages such as PSCAD like has been demonstrated in the current project. The models designed and implemented in this project provide a platform for current and future research into these microgrid control schemes to help implementation of more secure and stable networks.

### VII. Recommendations

The scope of this project was limited to implementing microgrid networks using PV RESs. As stated in section one, MGs can be comprised of various DERs such as wind, fuel cells, ESS, electric vehicles storage interface and reciprocating engines. Expanding and implementing these forms of DERs into PSCAD models will provide additional research and analysis into the control dynamics different DERs contribute to microgrids.
Islanded control scheme used in this project was based on communication-based control signals. Communication-based control can lead to decreased microgrid reliability, security concerns and limit DG expansion and flexibility [7]. Implementing communication-less control through schemes such as frequency signal injection will provide researches additional simulation platform.
References


