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Provisioning a 3.3 MW PhotoVoltaic Generation System onto a Distribution Authority’s 11 kV rural feeder

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Abstract: This paper describes part of an engineering study that was undertaken to demonstrate that a multi-megawatt Photovoltaic (PV) generation system could be connected to a rural 11 kV feeder without creating power quality issues for other consumers. The paper concentrates solely on the voltage regulation aspect of the study as this was the most innovative part of the study. The study was carried out using the time-domain software package, PSCAD/EMTDC. The software model included real time data input of actual measured load and scaled PV generation data, along with real-time substation voltage regulator and PV inverter reactive power control. The outputs from the model plot real-time voltage, current and power variations throughout the daily load and PV generation variations. Other aspects of the study not described in the paper include the analysis of harmonics, voltage flicker, power factor, voltage unbalance and system losses.

1 Background

AGL Energy Limited was announced in June 2013 as the successful bidder for funding under the Australian Government’s Solar Flagships program, which had the ambitious goal of investing $1.5 billion into commercial solar projects. First Solar will design and construct the solar power plants for AGL using its thin-film CdTe PV modules. The plants total 159 MWac, and will be located at Nyngan (106 MWac) and Broken Hill (53 MWac). These are due for completion in 2015 and will have an estimated capital cost of $450 million [1].

The project also includes a research component under the Education Infrastructure Fund (EIF), involving The University of Queensland (UQ) and the University of New South Wales (UNSW).

Part of this EIF infrastructure is the Gatton PV Pilot Plant – a 3.3 MW pilot PV plant will be built at UQ’s Gatton Campus (~100 km west of Brisbane)[2]. Construction is expected to be completed by December 2014 to facilitate knowledge sharing between UQ, UNSW, AGL and First Solar prior to completion of the Broken Hill and Nyngan solar plants.

The Gatton PV pilot plant will provide significant on-site renewable energy generation with surplus electricity being exported to the grid. This required a review of the existing UQ Gatton Campus connection agreement with the local distribution network service provider (DNSP), Energex. Energex responded indicating that the existing 11 kV campus connection was not a feasible option for the new PV pilot plant, rather a new connection to Energex’s existing 33 kV network would be required and would be suitable for generating capacity up to 5 MW. UQ commenced the high
level design of a 33 kV connection and 33/11 kV substation at the UQ Gatton campus.

Escalating costs of this proposed 33 kV connection and 33/11 kV substation led UQ to review the feasibility of connecting the PV array using one of the existing 11 kV connections. Moreover, this 11 kV connection has great research potential for all stakeholders and the community in general.

Energex proposed that UQ lead the required study to determine if an 11 kV connection was feasible. In summary, the study was required to prove the following:

- The existing 11 kV steady state voltage regulation and voltage envelope along the 11 kV feeder would not be exceeded;
- The voltage regulation and voltage envelope of other 11 kV feeders supplied from the Energex substation would not be compromised. The impact on Energex Gatton substation line drop compensation had to be considered;
- Series voltage regulator settings under both forward and reverse power flow would be studied;
- The power factor would not be compromised to the extent that it adversely impacted on the power factor at the upstream 33 kV connection point with Powerlink Queensland;
- 11 kV feeder losses would not be increased;
- Voltage fluctuations on the 11 kV network would be maintained with in the requirements of AS61000.3.7 and the National Electricity Rules;
- Voltage harmonic distortion on the 11 kV network would be maintained with in the requirements of AS61000.3.6 and the National Electricity Rules; and
- Voltage unbalance on the 11 kV network would be maintained within the limits set by the National Electricity Rules as defined in table S5.1a.1;

This list of potential network impacts and possible solutions are discussed along with a broader discussion of policy implications in the review papers by Passey et al [3] and Braun et al [4]. This paper concentrates solely on the voltage regulation aspects of the study.

2 Study inputs and model construction

2.1 Location of site and source of supply

The UQ Gatton Campus is currently supplied at 11 kV from the Energex Gatton zone substation via an 11 kV overhead feeder shown in green on the annotated geographic feeder diagram in Figure 2-1. Gatton Substation consists of two 25 MVA 33/11 kV transformers and associated 33 kV and 11 kV indoor switchgear. Gatton Substation is in turn supplied from the 110/33 kV Gatton Bulk Supply (not shown) via two 33 kV overhead feeders.

The main UQ supply connection point to the 11 kV overhead feeder and associated metering unit (MU3) for the campus is via Lawes Siding on the southern edge of the campus. The back-up supply connection point and metering unit (MU2) is adjacent to the Warrego Highway. Under normal distribution network operating procedures, only one connection will be used by the campus; the other will be open circuit.

Two Step Voltage Regulators (SVRs) are in-line with the two major branches of the 11 kV feeder along both routes to improve the voltage regulation for points remote from Gatton Substation, as indicated in Figure 2-1. The feeder splits into two major branches (Point A), with the majority of the customers being on the Warrego
Highway branch, leaving UQ Gatton and a few other consumers on the Chadwick Road branch.

A detailed electrical model of the 11 kV feeder, Gatton substation and UQ campus load was constructed using the power systems tool PSCAD. The static and dynamic voltage profile along this portion of network was assessed using this tool.

![Annotated geographic feeder diagram of the GTN5B 11kV feeder supplying the UQ Gatton Campus.](image)

**Figure 2-1** Annotated geographic feeder diagram of the GTN5B 11kV feeder supplying the UQ Gatton Campus.

### 2.2 Load levels and generation levels at the UQ site

The daily power curves for the UQ Gatton campus load, projected UQ Gatton PV 3.3 MW generation and the combined UQ Gatton campus load and PV generation are shown in Figure 2-2. These daily power curves show the maximum, average and minimum values for each half hour interval over the year long period of 1 July 2011 to 30 June 2012. These curves are based on actual measurements at UQ Gatton (UQ Gatton load), and on actual AC side meter measurements from the UQ Gatton 24.4 kWp PV array (a fixed plane array tilted 30° to the horizontal, and oriented 7°E of N), scaled to a future installed capacity of 3407 kWp (all currently installed and planned PV on the campus).

The final composition of the 3.3 MW PV array will include both single and dual-axis tracking arrays. While this will change the overall shape of the load generation from that modelled, the peak generation during the middle of the day will not be greatly affected; rather the morning and afternoon ‘shoulders’ will be filled out. Thus, scaling the existing fixed array was judged to provide a reasonable basis for the analysis undertaken.

The UQ load and PV curves (Figure 2-2 left, middle) are generated by summing each half hour value across the year. Note that the maximum (minimum) combined values (Figure 2-2 right) are not equal to the sum of the maximum (minimum) load.
and maximum (minimum) PV generation values, since these values are not co-
incident. Each of these curves present the maximum, minimum and average values
for each half hour, however note that they do not necessarily represent a daily load
or PV curves on a maximum or minimum day. This is highlighted in Figure 2-4.

Also shown is the corresponding yearly demand curves (Figure 2-3), created by
sorting all 17568 (366*48) half hourly values from maximum to minimum. The net
yearly demand curve is shown again in Figure 2-4, but with the corresponding load
and PV data points which created each net load point sorted and plotted with those
points.

Figure 2-2 The UQ Gatton campus load (left), projected UQ Gatton PV 3.3 MW generation (centre) and the combined UQ
Gatton campus load and PV generation (right) plotted as kW versus hour-of-day.

Figure 2-3 The load duration curves for the year for the UQ Gatton load (blue), PV (red) and combined load and PV
generation (green). The first and last percentile of the total year (each totalling 88 hours) are expanded to show the extreme
values.
Figure 2-4 The net load duration curve for the year for the UQ Gatton combined load and PV (green). For each net load data point, the corresponding load (blue) and PV generation (red) points are shown sorted with the net load.

2.3 Regulation of 11 kV feeder voltage using reactive power

The key technical concern of connecting a 3.3 MW PV system onto a rural 11 kV feeder is the potentially poor voltage regulation experienced by both UQ but also other customers sharing this feeder.

The power output of the PV array can potentially vary rapidly from 100% to 10% and back to 100% as clouds pass. Note that ‘rapidly’ is a relative term; for a large distributed PV array such as this 3.3 MW array proposed, rapid equates to a number of seconds.

The 11 kV feeder from Gatton Substation to UQ Gatton, is over 7 km long, and has a relatively high impedance. As the power imported or exported swings rapidly, the voltage drop at points more distant from Gatton Substation may also swing rapidly.

This issue can be addressed by the use of reactive power. Transmission lines such as the 11 kV feeder in question have an impedance which comprises both real (ohmic) resistance and inductive reactance. Real power flow (where the alternating current is in phase with the voltage) causes a voltage drop over the resistive portion of the line impedance. Reactive power flow (where the alternating current is 90 degrees out of phase with the voltage) causes a voltage drop across the reactive portion of the line impedance. Importantly, leading or capacitive reactive power flow (where the current leads the voltage by 90 degrees) causes a negative voltage drop – that is a voltage rise – across the reactive component. If the real power flow (measured in kW) and the reactive power flow (measured in kVAr) are kept in the correct ratio, the voltage drop caused by the real power flow and the voltage rise due to the reactive power flow “cancel”. This remains true if the real power varies, so long as the reactive power maintains the appropriate ratio.

The solar grid connect inverters can be programmed to vary their reactive power production in step with their varying real power production. The specification for the PV inverters calls for a minimum power factor capability of 0.9 leading to 0.9 lagging at rated power. This requires a 111% kVA rating of the inverters for a given PV AC power export rating, but allows the inverter to import or export 43% of its power rating as reactive power. The capabilities of an example SMA central converter which meets these specifications are presented in Figure 2-5 [5].
For a total inverter power capability of 3.3 MW, 3.67 MVA of inverter capacity would be specified (spread across multiple inverters), capable of simultaneously exporting 3.3 MW of real power and 1.6 MVAr of reactive power.

Figure 2-5 The SMA Sunny Central 800CP has an 800 kVA rating at 50°C, and 880 kVA rating at 25°C. At 25°C for power levels below 800 kW, it can produce or consume up to 380 KVAr of reactive power.

The programmed curve used in this study is shown in Figure 2-6. It uses a smaller portion of the available reactive power capacity of the inverters, from 750 kVAr reactive power export at 0 MW inverter generation, to 750 kVAr reactive power import at 3000 kW of inverter export. The parameter which is important for minimising the variation of feeder voltage drop vs. power swings is the ratio of reactive power swing to real power swing – the slope of the line in Figure 2-6. The intercept is somewhat arbitrary and can be chosen to optimise the overall system power factor.

As the PV system exports more and more real power, reactive power is absorbed by the inverters to suppress voltage rise. As PV generation approaches zero, the inverters produce reactive power to support line voltage because the site load is now being supplied from Gatton Substation resulting in voltage drop down the line.
3 Study methodology and results

3.1 Methodology

The voltage regulation study was conducted by constructing a time domain simulation model of the 11 kV network and proposed solar generation. PSCAD/EMTDC was used to undertake the simulation.

System impedance data, voltage regulator settings, capacitor bank settings and 30 minute load data for the entire 11 kV network, was collected from Energex. For the same time period, 30 minute load data for UQ Gatton was collected from site meters. 30 minute solar generation predictions for the new PV installation were made based on scaling existing recorded PV generation data on the site, for the same time period as the Energex load data, to give a realistic correlation between network load and solar generation (based on the weather conditions that existed at the time).

The time domain simulation was run using a number of two day snapshots of data, which represented maximum, typical and minimum network loading scenarios in order to study a wide range of possible conditions, so as to capture the worst case outcomes.

3.2 PSCAD voltage regulation assessment

The actual recorded 30 minute load data from the Energex network and UQ campus, along with the estimated PV generation data was input to the PSCAD file in real time. This allowed half hourly and daily load and generation variations to be studied, including the actions of all of the voltage control systems.

A number of indicative two day periods were studied. These selected days included:

- Two high load days for both the network and campus (10 to 11 November 2011) without PV (Figure 3-1) and then with PV (Figure 3-2)
- Two peak load days both for the network and campus (27 to 28 December 2011) without PV and then with PV
- Two low load days both for the network and campus (1 to 2 January 2012) without PV and then with PV. The combination of low campus load and full sun on 1 January demonstrated the effects of peak export on the lightly loaded network.

These days cover the extremities of expected operation. Only one of these (high load days) is presented in this paper as an example, first without, and then with PV generation. Shown in these figures (top to bottom) are:

- The real and reactive power flows at Gatton Substation (SSGTN) and Gatton Bulk Supply (GBS)
- 11 kV voltages at Gatton substation bus (set point and actual), Point A (where the 11kV feeder branches), MU3 (Energex connection point to UQ), and UQ Gatton internal 11kV substation (Sub0)
- The real and reactive power flows for UQ as a whole and for the UQ PV inverters
- Finally the tap changer and capacitor states for Gatton Substation, UQ Gatton and the SVR on Chadwick Rd (SVR A).
Figure 3-1  Two high load days (10 to 11 November 2011) without PV (print in colour)

Figure 3-2  Two high load days (10 to 11 November 2011) with PV (print in colour)
3.3 Voltage regulation discussion

The 11 kV voltage at Gatton Substation bus is regulated by a voltage regulator which controls the tap changers on the 25 MVA 33/11 kV transformers. This voltage regulator includes Line Drop Compensation (LDC). The existing Gatton Substation voltage set point is a constant 11 kV at total substation loads below 4.3 MW, then rises linearly to 11.4 kV (103.6 pu) at 17 MW, where it once again remains constant for further load increases. This increase in voltage with increasing power drawn from the substation partially compensates for the increased voltage drops along the various 11 kV feeders. The tap changer hysteresis window is 266 V (2.44%) centred on the voltage set point.

The Gatton Substation 11 kV bus is the point of common coupling for the majority of Gatton Substation’s load on all feeders other than the feeder connecting UQ. Thus the voltage regulation of the majority of Gatton Substation’s load on all feeders other than UQ’s feeder is influenced by UQ Gatton’s impact on the voltage regulation of the Gatton Substation 11 kV bus. The worst case transient impact is due to the sudden loss of sun and thus PV generation. The passage of a cloud across the sun during the middle of the day will drop the output from perhaps 90% of rating to 10 to 20% of rating, but not zero. However, to be conservative, we have assumed this loss of generation is a rapid fall from 3 MW to 0.0 MW over the space of a few seconds; a time which is shorter than the tap changers can respond. This variation brings about transient step responses. These are seen to be less than 1% at Gatton Substation 11 kV bus for all scenarios modelled for conductor temperatures of 50°C (the temperature at which they will actually operate) due to the application of reactive power control by the inverters.

As the Gatton Substation transformer hysteresis band is currently 2.44%, the majority of transient voltage changes (< 0.8% for a 100% to 10% PV generation change) will not cause the Gatton Substation transformer 11 kV bus to move outside its hysteresis band and thus outside the 11 kV bus voltage specification. If a transient voltage change does initiate a tap change, the 1.25% tap change step will move the bus voltage to approximately the middle of the hysteresis band, and subsequent transient voltage changes in the short term will not cause subsequent tap changes. The number of tap change operations are not increased by the introduction of the PV system by inspection of the simulation results.

The worst case steady state impact seen at Gatton Substation 11 kV bus will be due to the LDC settings of the voltage regulator. A change in power levels at this bus from 4.3 MW to 17 MW results in a change of voltage set point from 11 to 11.4 kV (3.6%). This is a voltage increase of 0.283% for each 1 MW increase, or 0.85% decrease for a 3 MW decrease in substation load. This will be the maximum average decrease in voltage on the bus at noon on cloudless days, assuming 3 MW of PV generation. In a number of simulations generated, this average fall in bus voltage while apparent in the Gatton Substation set point is difficult to see in the actual voltage due to the 2.44% hysteresis window of the tap changer.

If the magnitude of this steady state drop is deemed too large, it can be compensated by one or a combination of the following measures:

- Reprogramming or reconfiguring the voltage regulator LDC to reduce or remove the UQ 11 kV feeder power flow from the total Gatton Substation 11 kV power flow measurement;
- Reprogramming or reconfiguring the voltage regulator LDC to react to reactive as well as real power flow (as the Cooper Power System voltage regulators do);
- Reprogramming the voltage regulator LDC parameters to have a lower LDC slope; and
- Installing series voltage regulators on affected rural feeders, if necessary.

Note that any loads on feeders which are connected beyond a series voltage regulator will not be affected by the changes at Gatton Substation due to the correction provided by their local series voltage regulator. This is true for the majority of the (non UQ Gatton) load on the 11 kV which lies beyond the second series voltage regulator (SVR B).

4 Conclusion
The study concluded that an 11 kV connection is feasible provided that reactive power control is implemented within the inverters. Further enhancement could be provided if Energex undertook some control system modifications within their transformer tap changer and LDC system. The results were compelling and Energex has since permitted an 11 kV connection to be pursued. A collaborative working relationship between Energex and UQ is developing and it is hoped that learnings from this project will benefit all participants. Whilst this is the first of such large scale PV connections in Energex’s network, it will provide learnings for future connections.

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