Generation Modeling of Residential Roof-top Photo-Voltaic Systems

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ABSTRACT

Environmental considerations have led to rapid uptake of domestic photo-voltaic (PV) systems in many parts of the world. PV intermittency and unpredictability have presented new challenges to the electricity distribution network service providers. The outputs of these domestic PV systems cannot be determined by their DC rating alone but are dependent on a number of installation and environmental parameters. A simplified model of PV kW output in response to solar irradiance and ambient temperature is developed in this paper. The model does not require detailed experimentation and testing of individual PV units. Accuracy of the proposed model has been verified using smart meter data and its potential applications for electricity distribution networks are demonstrated.

I. INTRODUCTION

Environmental considerations have resulted in world-wide government policies that encourage the connection of renewable energy sources to the public electricity distribution networks, notably photo-voltaic (PV) systems. In Australia, generous feed-in-tariffs (FITs) have resulted in exponential growth of PV systems that are mounted on the roofs of domestic premises. The distributed nature of these embedded generation, the limitation of existing electricity distribution networks (especially low voltage networks) to cater for bi-directional power flow, and the intermittency of solar generation have contributed significant challenges to utility engineers.

To understand the effect of a single PV installation on the distribution network, very detailed models of PV system have been established using electrical representations of the various components that make up the PV installation (e.g. solar panels, inverter, associated wirings etc.). The PV system output is then modeled based on how these components interact with external factors such as solar irradiance, ambient temperature and wind speed, while taking into account panel orientation, solar cell efficiency and electrical losses [1],[2],[3].

In a public electricity distribution network, the parameters required to determine these electrical models are not generally known in details as the PV panels are part of private customer installations. Hence a new approach to developing practical models of solar generation is needed.

This paper is organised as follows: in Section II a description of typical PV system output based on recordings from smart meters is given; Section III derives a PV output model based on solar irradiance, ambient temperature and panel DC rating; Section IV deals with the solar irradiance component that is used in the PV output model; applications of the PV output model to practical distribution network issues are given in Section V; finally conclusions and suggestions for further work are given in Section VI.

II. PRACTICAL PV SYSTEM OUTPUTS

The Australian electricity distribution company, which contributes data to this research project, captures the following information in domestic grid-connected PV installations: (a) PV panel dc rating (kW), and (2) PV inverter rating (kVA), model, make and number (if more than one inverter are installed). It is worthy to note that PV panel ratings are defined under standard test conditions (STC) of 25°C cell temperature, direct solar irradiance of 1000Wm² and air mass of 1.5 (i.e. terrestrial condition). Significant variation in PV panel output from STC rating occurs in practice, as illustrated in Fig. 1 where maximum outputs of a number of PV systems are shown for each month of a year. For these systems installed in the state of Victoria, Australia, they typically produce output power less than the PV panel ratings, even in summer months when the outputs are at the highest.

For utility engineers to assess the impact of PV system on the supply network, they need a kW output model with parameters that are readily available.

III. PV OUTPUT MODEL

Departure from STC rating of PV system arises from the
following causes:

- Solar irradiance falling on the PV panel surface exhibits both daily and seasonal variation due to the changing angle of the sun’s ray;
- Solar cell output exhibits a negative temperature coefficient with respect to cell temperature. The process where sunlight is converted into electricity is therefore less efficient on a hot day than a cold day;
- Loss of efficiency due to electrical losses in wirings/inverters, component ageing and soiling/shading from dirt buildup and nearby tall structures;
- Cloud cover affects the amount of solar irradiance that reaches the PV panel surface. This is the primary factor that accounts for the stochastic nature of solar generation.

Cell temperature of a solar installation is not a parameter that can be easily measured. A simplified empirical formula linking ac inverter output of a PV array to ambient temperature and solar irradiance is given in [4]

\[ P_{ac}(t) = P_{SRC} \times \frac{G_{ROA}(t)}{1000} \times [1.125 - 0.005t_a(t) - 0.000175G_{ROA}(t)] \times \eta \]  \hspace{1cm} (1)

where \( P_{ac} \) is the ac output of the PV inverter, \( P_{SRC} \) is the PV panel dc rating specified at STC, \( G_{ROA} \) is the plane of array solar irradiance in Wm\(^2\), \( T_a \) is the ambient temperature and \( \eta \) is the dc/ac conversion efficiency (which includes the inverter efficiency, dc losses, soiling and ageing of the PV array).

Equation (1) can be used to model the ac output of a PV system using only ambient temperature, solar irradiance and dc/ac conversion efficiency. There are a few conditions for its use:

- It is a quasi steady-state equation and cannot be used to determine the transient response of a PV system to sudden changes in solar irradiance. The Maximum Power Point Tracking (MPPT) algorithm incorporated in the inverter dominates the dynamic behavior of the PV system and has not been taken into account in the equation; [6] [7]
- DC/AC conversion efficiency is dependent on the amount of solar irradiance, soiling and ageing of the PV panels, dc losses, inverter design and the amount of input power relative to the inverter rating. The maximum ac output of a PV system normally occurs at maximum solar irradiance where inverter efficiency is at its highest and a nominal dc/ac conversion efficiency of 0.85 to 0.9 can be assumed [8]. For energy yield calculation, [9] recommends an overall system derate (or efficiency) of 0.77.

IV. SOLAR IRRADIANCE DATA

The plane-of-array solar radiation is made up of two components, a direct component resulting from the sun’s direct beam, and a diffuse component resulting from scattering of the sun’s beam due to atmospheric constituents. It can be expressed as below [5]:

\[ G_{ROA}(t) = G_{Dir}(t) \times \cos(Y(t)) + G_{Dif}(t) \times (1 + \cos A)/2 \]  \hspace{1cm} (2)

where \( G_{Dir} \) is the direct irradiance measured in a plane normal to the sun, \( G_{Dif} \) is the diffuse irradiance measured in the horizontal plane, \( A \) the inclination of the array from the horizontal, and \( Y \) is the angle of incidence, between the direction of the sun’s ray and the array normal, and is also known as the sun’s zenith distance.

It is shown in [4] that equation (2) can be further simplified by replacing \( G_{ROA} \) with global irradiance \( G_{GLO} \), defined as the total solar irradiance (both direct and diffuse) measured in the horizontal plane, with only minor loss in accuracy.

Equation (1), which gives the output of a PV system, can be expressed in \( G_{GLO} \) as

\[ P_{ac}(t) = P_{SRC} \times \frac{G_{GLO}(t)}{1000} \times [1.125 - 0.005t_a(t) - 0.000175G_{GLO}(t)] \times \eta \]  \hspace{1cm} (3)

Equation (3) can be used to determine the kW output of a PV system when global irradiance and ambient temperature is known at the PV install location.

V. DISTRIBUTION NETWORK APPLICATIONS

A. Solar irradiance data at PV install locations

The solar irradiance falling on the PV array of a residential customer is not generally available. To get around this limitation, tools developed to determine the sizing of PV arrays and payback generally use historic solar statistics by establishing metrics such as Typical Meteorological Year (TMY) for a particular region/country [9]. These solar irradiance data are useful for benchmarking the annual energy yield of various PV systems. They are however unlikely to predict accurately solar irradiance on shorter
time horizons such as daily or hourly. The Australian Bureau of Meteorology has a number of weather stations that measure solar irradiance in time intervals of second (averaged over a minute). The weather station located at Tullamarine International Airport is in the geographical centre of the electricity distribution network where these PV systems are installed (Fig. 2). The solar irradiance recorded at this weather station [10] is used as the ‘proxy’ for the solar irradiance received by PV system located in any part of the electricity distribution network.

Detailed study indicates that lower values of correlation coefficients (e.g. ≤0.8) occur on days where there is significant cloud coverage (indicated by significant diffuse solar component relative to global solar component). Two examples are shown in Fig. 3 and 4.

To prove the validity of this assumption, a linear correlation study is performed between the global solar irradiance daily dataset and the generation daily dataset of a 1kW PV system installed in the distribution network, over a one-year period (2012). As the generation dataset is only available in 30-minute aggregate values, the 1-second solar irradiance data (Wm⁻²) are firstly aggregated to form 30-minute solar irradiance energy (Jm⁻²). The MATLAB function `corrcoef` is then run for the data matrix (where each column represents a separate quantity). A positive linear relationship between the data columns will return a matrix of correlation coefficients with values close to 1. The correlation coefficients are summarized in Table 1. From Table 1 it can be seen that strong linear correlation exists on most days of the year.

<table>
<thead>
<tr>
<th>Value of correlation coefficient</th>
<th>Days</th>
<th>Percentage of days in 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;=0.95</td>
<td>183</td>
<td>51.5%</td>
</tr>
<tr>
<td>&gt;=0.90</td>
<td>257</td>
<td>72.4%</td>
</tr>
<tr>
<td>&gt;=0.85</td>
<td>306</td>
<td>86.2%</td>
</tr>
</tbody>
</table>

The observation above can be explained by the fact that solar irradiance on clear-sky days is dominated by direct solar irradiance component and one would expect that this direct component will be experienced by PV panels installed in relatively close proximity to the weather station. On a cloudy day, however, solar irradiance has a significant diffuse component. This diffuse component is caused by scattering of the sun’s rays by cloud and surrounding objects, including reflection from the ground. The diffuse component can show significant variation depending on the local site condition.

Similar observation is obtained from analysis of other PV sites. It is therefore concluded that the solar irradiance data at the Tullamarine weather station is a good ‘proxy’ to model the solar irradiance received by a local PV system on a clear sky day, when the diffuse solar irradiance contribute less than 20% to the global solar irradiance.
Solar forecasting is under active research currently. It is possible that accurate forecasting models will become available soon which can then be used as ‘proxy’ to forecast the output of PV systems [11].

B. Modelled and actual output of a PV system

Equation (3) provides the quasi steady-state output of a PV system at any time t, provided the global solar irradiance and ambient temperature at that instance in time are known. While instantaneous value of the PV system output is useful for power quality impact assessment, utility planning engineers are more interested in ‘average’ PV output over a time interval, typically 30-minute, as this aligns with the thermal inertia of equipment commonly found in electrical power networks. This can be achieved by adding the calculated PV output, at every second, over a 30-minute interval, then dividing the summation by the time interval (1800 seconds):

\[
\frac{\sum P_{ac}(t)}{1800} = P_{stc} \cdot \eta \cdot 0.001 \cdot \frac{1}{1800} \\
\times (1.125 \cdot \sum G_{ glo}(t) - 0.005) \\
\times (\sum (G_{d}(t) + G_{ glo}(t)) - 0.000175) \\
\times G_{ glo}(t)2
\]

For the time varying quantities on the right-hand side of (4), global solar irradiance \( G_{ glo} \) is available from the Bureau of Meteorology weather station, ambient temperature measurements are only available as 30-minute snapshots however this is considered acceptable as ambient temperature does not exhibit rapid variation. Finally for maximum output determination, we’ll take the efficiency \( \eta \) as 0.9.

30-minute generation output of the 1kW PV site is determined using (4), and compared with the measured generation output. The results for 2 days in January are shown in Fig. 5 and 6. On 2 January the sky was overcast (shown by the high diffuse to global solar irradiance ratio) whereas the sky was relatively clear on 6 January. It can be seen that (4) gives accurate estimate of 30-minute generation output when cloud cover is minimal, reinforcing the observation made in Section (A) above.

It should be noted that the error of (4) is larger at low PV output. This is due to the fact that PV inverter is generally less efficient at low power (corresponding to low solar irradiance level early in the morning or late in the afternoon) [8]. This is not considered as a limitation when (4) is used for the purpose of determining the maximum output of a PV system.

It can be concluded that the output of a PV system can be estimated accurately by the proposed method, provided the solar irradiance data used in the calculation (and measured at a nearby weather station) has only a small diffuse component, and that the solar system is operating at reasonable high output level relative to its rating.

C. Gross metering and net metering

Many PV sites in Australia has net metering applied where a single meter (with separate export and import registers) is used to record the aggregate power flow into or out of the point of connection. In effect PV generation is treated like ‘negative’ load in a net metering setup. While net metering is generally more advantageous for customers in the absence of favourable FIT (generation that offsets internal consumption is effectively paid at the same rate), net metering data cannot be readily dis-aggregated into generation and load data. This has a negative impact on the accuracy of load forecasting when significant penetration of domestic PV generation has occurred, as the two components (load and generation) could be influenced differently in future scenario. For example, customer loads generally go up on hot summer days due to the use of air conditioning. In Victoria, Australia, however, many high temperature days are coincident with high cloud cover which reduces the output of PV generation. PV generation is also less efficient on hot days. Accurate load forecasting would need to apply different influencing factors to the load and generation components.
The proposed PV model can be used to disaggregate net load profile into generation and load components. Fig. 7 below shows an example output:

![Figure 7. Estimated and measured load profile for a 1kW PV site](image)

VI. CONCLUSION & FURTHER RESEARCH WORK

One of the major challenges faced by the electrical supply industry in accommodating customer photo-voltaic installations today is delivering secure, reliable and high quality power while managing fluctuations and intermittency of the energy source. Meeting the challenge requires information on solar resources as well as other data on parameters affecting the solar output.

This paper provides a model to determine the in-situ output of roof-top PV systems installed on domestic premises. The methodology is based on dc rating of the PV system, ambient temperature and solar irradiance data. To overcome the challenge posed by the lack of local measurements of solar irradiance data, covariance analysis has confirmed that data captured in a nearby weather station can be used provided the sky is relatively clear. While this constraint may seem to be limiting, the methodology is applicable to electricity network planning studies which have the focus on extremes (such as maximum solar irradiance and clear sky) rather than averages.

As penetration of PV system increases in electricity distribution network, it would be necessary to disaggregate load measurements captured by monitoring systems (such as smart meters and Supervisory Control and Data Acquisition SCADA) into solar generation and load consumption. This will allow the appropriate drivers to be incorporated into the analysis of historic data and future forecast. In this regard, it is important to point out that load demand in Australia is generally driven by air conditioning use during hot summer days, whereas solar output is reduced at high ambient temperature and cloud coverage.

The proposed PV model can be incorporated in network load flow programs to assess the impact of individual PV installation on power quality parameters such as voltage and unbalance. Decision needs to be made with regard to appropriate use of solar irradiance and ambient temperature historic/forecast data. Studies of extreme cases may warrant the use of best/worst case combination of solar irradiance/ambient temperature/load combination. Probabilistic methodologies using Probability Density Functions of the stochastic variables may be more appropriate for nominal studies [12].

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REFERENCES


