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An Investigation of the Impact of Photovoltaic Generation on a Utility Transmission System

P. POURBEIK[1]
Electric Power Research Institute
USA

S. EFTEKHARNEJAD
Tucson Electric Power
USA

R. BELVAL
Tucson Electric Power
USA

SUMMARY

This paper provides a summary of the results of a recent study to investigate the potential impact of the large penetration of photovoltaic generation in the near future on a utility transmission system. The system studied is the transmission system of the Tucson Electric Power (TEP) utility. The analysis looked at both a near term and a longer term (10 year) case. The photovoltaic systems were modeled using generic models, with a reasonable representation of the dynamics of the power converters for stability studies. The bulk of the anticipated photovoltaic generation is expected to be installed at the distribution level, as such sensitivity studies were done to investigate the impact of allowing the distributed generation to trip (per IEEE Std 1547) and assuming that the generation is fitted with fault ride-thorough and thus not allowed to trip. The analysis, however, is focused on the impact of the distributed generation on the transmission system.

KEYWORDS

Photovoltaic Generation, Stability, System Dynamic Performance

1. INTRODUCTION

Presently, in several regions in North America, there is a full expectation that a significant amount of photovoltaic (PV) generation will materialize and become part of the generation mix. The Tucson Electric Power Company (TEP) has recently seen significant interest in interconnection of renewable resources, primarily PV generation. PV generation is variable by nature; that is, the energy source is variable due to fluctuating weather conditions primarily due to cloud formation and movement. PV generation is connected to the power grid through a power converter interface. As such, these factors can have considerable impact on system dynamic and operational performance. Examples of a recent studies related to the potential impact of PV generation on a transmission system can be found in [1] and [2]. What is presented here is focused analysis specific to the TEP system and performed using information on specific amounts and projections of the potential amount of PV that might be interconnected to the TEP system. Furthermore, a preliminary look is also taken at the effect

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[1] ppourbeik@epri.com or pouyan@ieee.org

of the variability of the PV generation on system frequency and voltage. The total amount of PV currently proposed within the five year planning horizon is in excess of 150 MW, and by 2022 is projected to reach levels of around 600 MW name plate capacity[2]. The goal of this study was to take a preliminary look at the impact of this proposed generation on the TEP transmission system. Since the system is usually susceptible to voltage instability and thermal constraints during peak load periods, the focus in this analysis was on looking at the system projected peak load periods.

2. STUDY ASSUMPTIONS AND MODELLING OF THE PV GENERATION

The primary concern at the onset of the study was voltage stability and thermal limits on the transmission lines. Hence, peak load conditions were the focus of the study for two future year scenarios (2015 and 2022).

2.1 Load Modeling Assumptions

For the purposes of this study, based on the recent decision of the WECC Modeling Validation Working Group (MVWG) the phase 1 new WECC composite load model was used [3]. This model was applied to the entire WECC system, using the WECC load model data tool (LMDT).In accordance with the current phase 1 release of the composite load model, we disabled stalling of the 1-phase air-conditioner motor load component. Furthermore, we disabled the tripping of any of the motor load components since there was no specific data available for these setting for the large number of loads in the system; this is a pessimistic assumption, but for now seemed the more reasonable approach. The default parameters were used for all other motor load and other load components. This is the recommended practice particularly in the case of the air-conditioner (a/c) loads, since in this case the parameters are based on laboratory tests of a/c units [4]. The complete composite load model is shown in Figure 1.

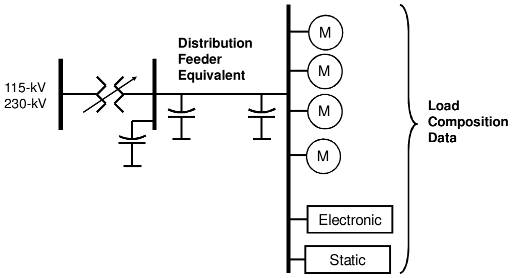

Figure 1: The WECC cmpldw load model.

2.2 Modeling the PV Generation

The Renewable Energy Modeling Task Force (REMTF), under the WECC MVWG, is developing a series of second generation generic models for modeling the dynamic behavior of PV generation in planning studies. These models were not yet available at the time of this study. Thus, for the purposes of this study we used the PV1G and PV1E models that were available at the time of this analysis (in 2012) in the current WECC approved simulation tool.

2.3 Power flow Representation

In power flow, the PV generation is represented as a constant real (P) and reactive (Q) generator at the appropriate transmission bus[3]. For the sake of simplicity, for the purposes of

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[2] These proposed MW numbers are based on information available in mid-2012, when this study work was done. These numbers may very well have changed by the time this paper is published.

[3] Utility scale PV connected to distribution feeders were modeled at the appropriate 138 kV distribution substations.

this study, all of the future PV generation was assumed to be at unity power factor holding constant reactive power at 0 MVAr.

2.4 Dynamic Representation

In the time-domain simulations all of the PV generation is represented using the PV1G and PV1E generic PV models. The same parameters for these models were used for all of the PV generators. A set of typical and reasonable values were used. The settings were chosen to:

1. Hold unity power factor and provide neither reactive support nor voltage regulation. This is a conservative assumption, but a reasonable on since the majority of the PV is distributed residential and small commercial units. Also, at this point it is not known what control strategies these future installations may employ.
2. To have real power priority, that is, to maintain the real power output of the unit constant and at the initial output level to the extent possible.

Figure 2 shows a brief schematic of the PV model used. The actual PV1G and PV1E model, when combined, are more complicated than what is shown in Figure 2. However, for the purposes of this study the parameters were chosen to essentially effect what is shown in Figure 2 (i.e. assumptions stated above).

Two sensitivity cases were simulated: (i) assuming that all of the PV is capable of riding-through a fault, and (ii) assuming that for a voltage dip of greater than 15 to 20% at the terminal of the PV unit it will trip and disconnect from the system. The reason for the second assumption is that per the present IEEE Standard 1547 [5], distributed resources may be allowed to trip for such voltage-dips. Therefore, the intent of these sensitivity runs was to see the effect of allowing or not-allowing the PV to trip following a fault.

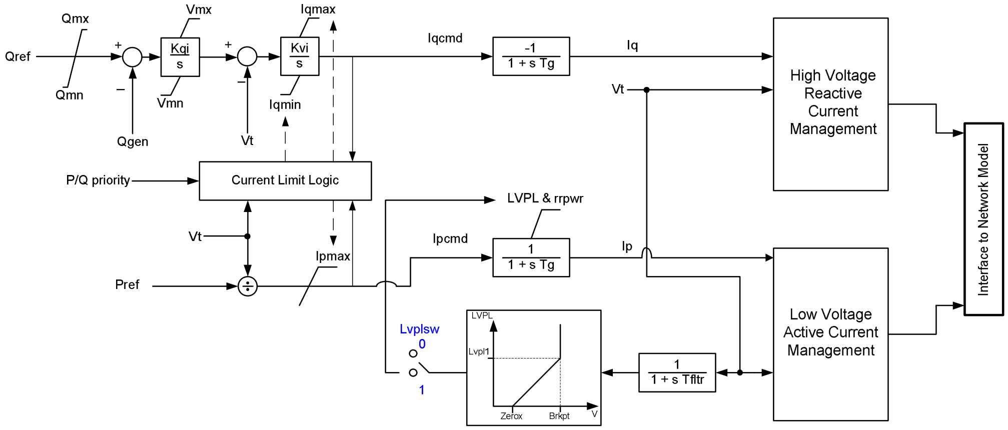

Figure 2: The PV model structure

3. SETTING UP THE PV GENERATION CASES

Based on a list of the projected amounts, and location, of both distribution and utility scale PV in the TEP area, for both 2015 and 2022, the power flow cases were augmented. We started with the original base cases (summer peak scenarios) and changed nothing in the TEP area except adding the new PV generation. In both cases, the new PV generation was dispatched against other generators in Arizona, but outside of the TEP control area. Figure 3 shows data for the largest real power swings in PV generation over a minute time frame as determined by a consultant that had performed the PV generation forecasting study [6]. This is during a hot summer day. Although not shown, the data also contains the change in the PV output at each of the respective TEP substations. For the purposes of the study two actions were taken with this data:

1. In each case we took the peak of the curve (roughly 220 MW in 2015 and 460 MW in 2022) and appropriately scaled the PV generation in the case to reflect this amount of generation. It is appreciated that this may not be exactly correct, since the day of this PV generation peak and peak-swing does not necessarily correspond exactly to the project peak-load day/hour. None-the-less, since present planning criteria are based on deterministic rules that require looking at the coincidence of peak load and peak generation from the facilities(s) under study, this can be a reasonable compromise, especially since the likelihood of all the PV generation being at peak name-plate capacity output at one time is quite low indeed. These cases represent the total PV generation in the system being at 70% and 74% of name-plate capacity in the two respective cases.
2. In both cases (2015 and 2022) a 60 second simulation was performed, in time-domain, by imposing on each of the buses in the system the various MW variations at the specific substations that result in the total PV generation swing shown in the first minute of Figure 3. This was done to get a rough indication of the resultant effect such variations may have on the system voltages and frequency. It must be understood, however, that the standard WECC system model is not necessarily adequate for such mid-term stability studies and this is only a rough indication of behavior.

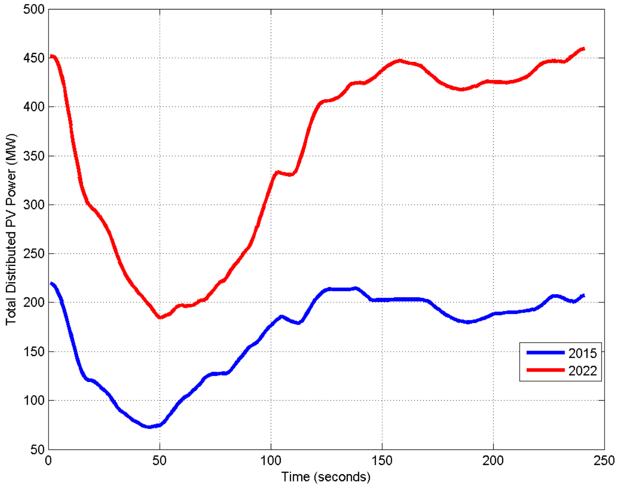

Figure 3: Plot of the largest swing in total installed PV generation on the TEP system, due to cloud movement– simulated day is June 21st. Source of the data is reference [6].

4. RESULTS OF THE STUDY

Power flow contingency and QV analysis was performed on all four cases (2105 and 2022 with and without PV). In general, there were no significant differences between the with- and without-PV generation cases when comparing the results of the power flow contingency analysis. The local generation dispatch was not adjusted to allow the PV to displace local thermal generation. If local thermal generation was reduced, this would result in adverse system impacts, in part due to reduced reactive resources.

The voltage profile is slightly higher in the case with the PV generation. System voltages are generally higher both before and after most contingencies. In general, this is a good result at the transmission level. In the future, however, more detailed analysis will be needed for lighter-load conditions (i.e. non-peak conditions), as under these conditions the additional generation from PV may potentially give rise to over-voltage conditions. Similar results have been seen in other studies [1].

These results are consistent since as more distributed PV is introduced onto the power system it effectively cancels out the load on the distribution feeders such that the resultant net load seen at the transmission level is reduced. Thus, transmission voltages will be slightly higher and there will be a reduction in the required reactive support at the transmission level. This also reduced the amount of MW imports thus reducing the loading on the EHV lines into the TEP area. It is important to understand that the models used for these simulations do not have an adequate representation of the distribution network. Therefore, this analysis cannot make any conclusions with respect to the impact of the distributed PV generation on the distributions system. In several cases the total anticipated distributed PV generation is significantly larger than the projected load at that substation. In these cases the flow on the distribution network will reverse at times of the day when PV generation is at its peak. Careful study of these parts of the distribution network is needed to ensure that the network can accommodate such conditions.

For the purposes of time-domain simulations the goal was to identify for the case of a major transmission fault and line outage how will the system voltages recover after the event? How is this affected by the presence of the PV generation? Is there a degradation in system damping or rotor angle stability due to the PV generation?

In all the cases we are assuming that for the duration of the transient stability simulations (i.e. 10 to 20 seconds) the output of the PV generation remains constant. In the presence of cloud movement, such an assumption is not valid, as is clear in Figure3. However, for clear sky days it is quite legitimate to assume, that the solar radiation does not change dramatically over a few second period. Since here we are interested in the system transient stability, for simplicity we make this assumption. It is shown later that even when the worst swing in PV generation output is simulated to represent cloud movement, that the variation in system voltages is roughly 1 percent or less, which is an order of magnitude less than those caused by transmission faults. In total 69 simulations were performed looking at various cases and sensitivities. It is not possible to present all these results in a short paper. The following high-level conclusions were derived from the results:

1. For nearby bolted 3-phase faults at the major EHV substations during heavy summer load the system behavior was consistent with previous studies [7]. PV did not help in these situations. The real issue is that there is not enough information on the exact load composition and the nature of protection on major industrial loads for the system to perform much more detailed analysis for 3-phase faults with such complex load models. Also, there is no historic data on these types of faults during summer peak loads to indicate what the actual system behavior is expected to be.
2. Assuming that all the PV generation is capable of fault ride-through, the voltage recovery of the cases with the PV generation in-service is actually better that the cases without PV generation. Figure 4 shows an example simulation of an N-1-1 event[4].

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[4] By definition an N-1-1 event is one where an N-1 event occurs, the system is readjusted and before the element is restored a second N-1 event occurs. Thus, the separation between the events is considered to be many minutes to tens of minutes. However, for the sake of simplicity the events are simulated here within 10 seconds of each other.

These results are consistent with the steady-state analysis which indicated that the system voltage profile is better with the PV generation and the reactive margins are also higher. This is because the added generation (PV) on the load feeders helps to support the voltage immediately after the disturbance.

3. In the case that we assume that the distributed PV generation trips for severe voltage-dips (i.e. no fault ride-through) the results are similar or worse than the case without PV generation (see Figure 4 for an example where the results are worse). This is expected since once the PV generation trips the load on the feeders has no local support and the system is back to the original behavior.
4. A close perusal of some of the cases shows that with the PV generation in the system the electromechanical modes of rotor oscillation on some synchronous generators are slightly less damped. An example of this is shown in Figure 5.

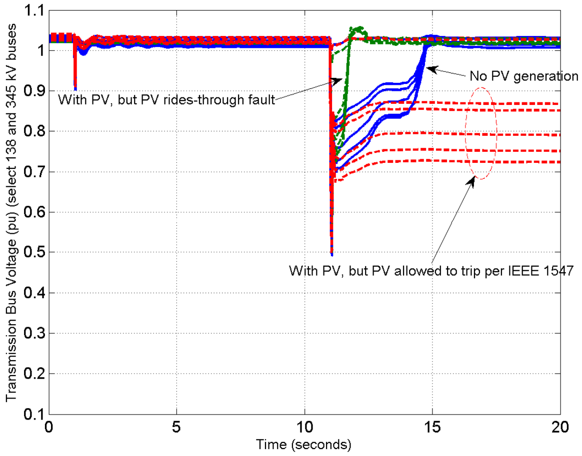

Figure 4: Plot of system voltage recovery due to an N-1-1 event. For simplicity the second outage is taken about ten seconds after the first.

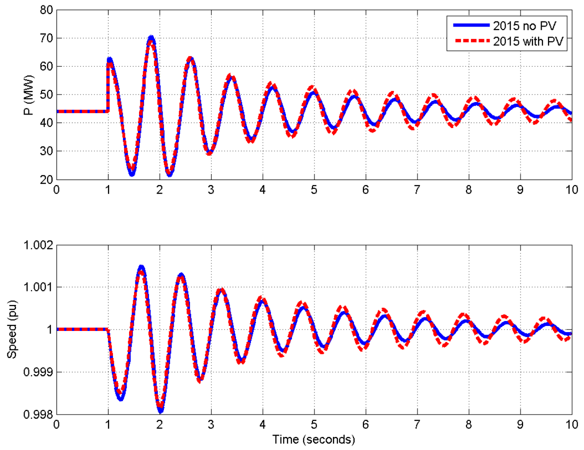

Figure 5: Plot of MW and speed oscillations on a local generator in the TEP area for a given disturbance, both with and without PV generation. PV does not trip in this case.

4.1 Simulation of the Time Variability of the PV Generation

In Figure 3 the worst-case second-to-second variation in total system PV generation for 2015 and 2022 was shown. In the first 60 seconds the steep drop in PV MWs occurs. Thus this period was simulated in by playing into each substation, in time-domain simulations, the second-by-second variation of MWs as a piece-wise linear curve. This was done for both the 2015 and 2022 cases. As an example, Figure 6 shows the results of these simulations for the 2022 case. The frequency traces shown in the figure are from key TEP buses

Here we are assuming that all other models are suitable for a 60 second simulation. This assumption is not entirely correct. With this limitation in mind a perusal of the results shows the following:

1. The variation in PV generation does impact both system frequency and voltage.
2. The change in frequency in the TEP system is about a 10 mHz drop for a 200 MW drop in power. The actual drop is a function of the total generation and reserves on-line, i.e. the same variation in MW may result in more or less system frequency variation under different load and generation dispatch scenarios.
3. The change in voltage is roughly 1% in 2015 and closer to 1.5% in 2022 for a 150 MW and 250 MW PV generation drop, respectively.
4. In both cases, but more pronounced in 2022, we see the TEP North East SVC [7] switching in capacitor banks many seconds into the event as the voltages drop and its respective reactive output increases to maintain system voltage.

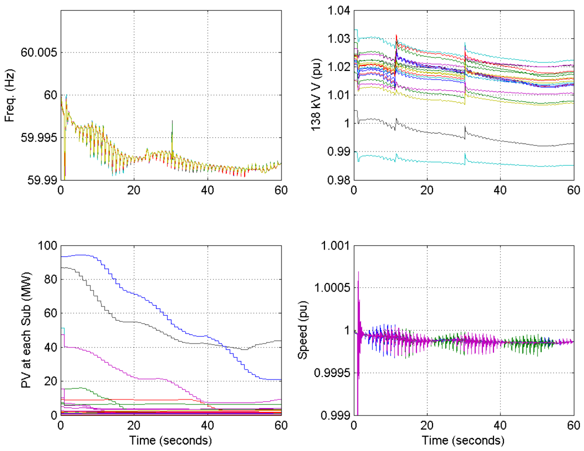

Figure 6: Results of simulation of the large swing down in the PV generation in the TEP area for the year 2022.

5. SUMMARY AND CONCLUSIONS

In this study two scenarios have been explored a 2015 and a 2022 summer case. In the 2015 case the total PV generation on-line was 10.8% and in the 2022 case it was 18%, of the peak load. This is based on information from a solar forecast study performed by a consultant. Steady-state and dynamic simulations were then performed with these two cases. The high-level results achieved were as follows:

1. The addition of the PV generation does not appear to have an adverse effect on system steady-state conditions. The PV generation was added in addition to the local TEP thermal generation; therefore the PV generation results in reduced imports. In general, steady-state voltages are improved since we have distributed PV at the major load buses, which means the net load as seen at the transmission level is lower and thus

voltages are higher and reactive margins are also higher than the same scenario without PV generation.

2. For the dynamic simulations we see that the system voltages, in general, recover faster and settle higher with the PV generation in the system, if we assume that all of the PV generation is able to ride-thorough transmission faults. However, if the PV generation is allowed to trip for pronounced voltage-dips, for near-by faults (i.e. on the 138 kV system) the system response can be worse than the cases without PV.

Another simulation that was performed in the two cases was to play the variability in the PV generation throughout the TEP system for the worst predicted second-to-second drop in PV power due to cloud movement. Noting the limitations of the WECC model to perhaps adequately capture such mid-term simulations a perusal of the results showed that the variation in PV generation does impact both system frequency and voltage. In our example we are simulating PV generation variability only in the TEP system. In the future, the total amount of variable generation (both wind and solar generation) will likely increase, dramatically, throughout WECC. Under these conditions, the most challenging aspect of the performance of these sources of generation will be operational, namely load/generation balance, frequency control, and voltage regulation. These are all manageable issues, but as indicated in the literature, they may start to present a challenge as the percentage of penetration goes beyond 20% [8]. A thorough analysis of these operational impacts is beyond the scope of the present work.

Finally, it may be prudent in the future when further more detailed analysis is performed to look at a light-spring case during which system load is significantly lower than the cases studied here. Such an analysis, particularly from a steady-state point of view, may be prudent in order to identify potential steady-state overvoltage conditions that may occur during peak hours of PV generation.

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