IMPACT OF A LARGE PENETRATION OF PHOTOVOLTAIC GENERATION ON THE POWER SYSTEM

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SUMMARY

As the concern over global warming increases, renewable energy sources have become a more significant source generation of electrical energy. Among these renewable energy sources, photovoltaic (PV) generation is attracting a growing amount of political and commercial interest. For example, the European Commission’s White Paper on renewable energy sets an indicative objective of 3GW of installed photovoltaic generation in Western Europe by 2010. Such a large penetration of distributed PV generation would have far reaching consequences on the power system. The effect of a large penetration of PV generation on the stability and security of the power system must therefore be considered carefully.

The first part of this paper describes a model of PV generation suitable for integration in a power system stability program. This model was developed on the basis of experimental results. It was found that the maximum power point tracking technique is the crucial element in the dynamic behaviour of the PV generation. Experimental results show that the model gives reasonably accurate results when used to predict the PV response following small changes in irradiance, sudden large changes in irradiances and sudden large changes in grid ac voltage.

The second part of this paper describes how the PV generation model has been used to analyse the impact on the power system of incorporating a significant amount of PV generation. It discusses the slow transient in bus voltages corresponding to fluctuation in photovoltaic generation resulting from the passage of clouds.

PV GENERATOR MODEL

Figure 1 gives an overview of the proposed PV generator model. $I_{pv}$ is the control variable and is calculated at each time step as the sum of four components:

- The value of $I_{pv}$ at the previous step
- The change $\Delta I_{pv}^{mppt}$ that reflects the action of the Maximum Power Point Tracking (MPPT) controller
- The change $\Delta I_{pv}$ that represents the effect of variations in irradiance
- The change $\Delta I_{pv}^{Vac}$ that represents the effect of sudden variations in ac grid voltage

$I_{pv}$ is one of the inputs to the block representing the non-linear characteristic of the PV array. The other input to this block is the irradiance $I$, and the output is $V_{pv}$. The block representing the MPPT has two inputs, $V_{pv}$ and $I_{pv}$, and one output, $\Delta I_{pv}^{MPPT}$. Finally, two blocks are used to represent the effect of sudden changes in irradiance and voltage. They take the magnitude of these sudden changes as their input and produce $\Delta I_{pv}^{Ir}$ and $\Delta I_{pv}^{Vac}$ respectively.

Flow Chart

While Figure 1 represents the interactions of the different parts of the model, the flow chart of Figure 2 illustrates software implementation of this model. Following the initialization of the variables $I_{pv}$, $I$, and $V_{pv}$, the model enters a loop with a cycle time of 0.2s. The first step in this loop is to determine whether there has been a sudden change in irradiance and the magnitude of the change $\Delta I_{pv}^{Ir}$. The...
magnitudes of the change $\Delta P_{pv}^{Vac}$ is calculated if necessary. The new value of $I_{pv}$ is calculated by adding these changes to the current value of $I_{pv}$ and this new value is fed into the PV array equation to determine $V_{pv}$ and $P_{pv}$. Finally, $\Delta P_{pv}^{MPP}$ is calculated by comparing the current and previous values of $P_{pv}$.

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Effect of Change in ac Grid Voltage

Figure 7 illustrates the modeling of the effects of changes in the ac grid voltage. If A is the operating point before the voltage disturbance, B is assumed to be the operating point immediately after an increase in voltage and C the operating point immediately after a decrease in voltage. While the behavior of the system is qualitatively similar for both cases, experimental results suggest that the quantitative effects are different. The changes in PV array currents are:

\[ \Delta I_{pv\text{Vac}} = -G \times \Delta V_{ac} \text{ for an increase in voltage} \]
\[ \Delta I_{pv\text{Vac}} = -0.25 \times G \times \Delta V_{ac} \text{ for a decrease in voltage} \]

where G is a constant number equal to 2.875 for the generator studied in this paper.

MPPT

This PV generation model assumes that the MPPT technique used is the Perturb and Observe (P&O) method. Instead of monitoring and controlling \( V_{pv} \), this model adjusts \( I_{pv} \) in its search for the maximum power point. The input to the MPPT model are \( I_{pv} \) and \( V_{pv} \). These two quantities are multiplied to obtain \( P(k) \), which is compared to \( P(k-1) \), i.e. the value obtained during the previous cycle. If the dc power delivered by the array has increased since the last measurement, the output of the MPPT will have the same sign as in the last cycle. On the other hand, if the power has decreased, the output of the MPPT will have the opposite sign to the last cycle. This output (+1 or −1) is multiplied by the \( I_{pv\text{MPPT}} \) step value, \( I_{pv\text{MPPT}} \), and added with the other components of the current \( I_{pv} \). The value of \( I_{pv\text{MPPT}} \) was determined by trial and error. If the cycle time is small, the \( I_{pv\text{MPPT}} \) will be relatively small. If the cycle time is big, the \( I_{pv\text{MPPT}} \) will be larger. In this model, the cycle time used is 0.2s, and the \( I_{pv\text{MPPT}} \) value obtained is 0.085A.

CASE STUDIES

These case studies illustrate the response of the system when subjected to a sudden change in irradiance caused by a passing cloud. Figure 8 is the diagram of the test system used in these examples. The system consists of a local area connected to a remote area by five 500kV transmission lines. All the loads (6668MW, 1910Mvar) are in the local area. Without PV generation, the local generator at bus 3 generates 1154 MW, and the remaining power is supplied by the two remote generators (bus 1 and bus 3) through five 500 kV transmission lines. Shunt capacitors are connected at various buses in the local area.

Five PV generators are connected to the local area of 13.8kV distribution circuit (bus 11 and bus 14) as shown in Figure 9.
Table 1: Generations produced by both the conventional generators and PV generation in the case of 10%, 20% and 30% level of PV penetration

<table>
<thead>
<tr>
<th>Bus</th>
<th>10% Penetration (MW)</th>
<th>20% Penetration (MW)</th>
<th>30% Penetration (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3291</td>
<td>2581</td>
<td>1876</td>
</tr>
<tr>
<td>2</td>
<td>1736</td>
<td>1736</td>
<td>1736</td>
</tr>
<tr>
<td>3</td>
<td>1154</td>
<td>1154</td>
<td>1154</td>
</tr>
<tr>
<td>11</td>
<td>335</td>
<td>670</td>
<td>1005</td>
</tr>
<tr>
<td>14</td>
<td>335</td>
<td>670</td>
<td>1005</td>
</tr>
</tbody>
</table>

Different amounts of PV penetration are considered in these case studies. Table 1 shows both the power produced by the conventional generators and the peak power of the PV generators for 10%, 20% and 30% penetration of PV generation. This system was simulated over a 60 seconds period on a typical partly cloudy day. In case study 1, all the 5 PV generators are assumed to receive the same irradiance, which is shown in Figure 10(a). The sampling rate of the irradiance data is 1 sample/seconds. A plot of the generation versus time for 10% PV penetration is shown in Figure 10(b).
Figure 10(c) shows the bus voltage versus time profile for a few selected buses within the system. Figures 11(b) and 11(C) show respectively the PV generation and bus voltages at bus 14 respectively for the three levels of penetration. Similar simulations were carried out in case study 2. However, as shown in Figure 12(a), the irradiance is shifted by 3 seconds for each of the 5 PV generators. Figure 12(b) shows the total amount of active power generated by the 5 PV generators into Bus 14. Figure 12(c) shows the bus voltages on busses 3 and 14. The comparisons between the PV generations and the bus voltages at bus 14 for the 3 levels of PV penetration are shown in Figures 13(b) and 13(c) respectively.

ANALYSIS

Figure 10 shows that the amount of power produced by the PV generators follows the pattern of irradiance. This is because the MPPT controller keeps the PV systems operating at their maximum power point despite the large fluctuations in irradiance that take place over the 60 seconds. Figures 10(c) and 12(c) confirm that the variation at the bus with conventional generators (Bus 3) is not affected by the fluctuation in PV output because of the action of the automatic voltage regulators. Bus 14 is connected to a PV generator. Its bus voltage fluctuates during the large change in irradiance level (between 3s and 25s). Its change follows the pattern of change in the total power at the bus. The PV generator is modelled as a P injector without a voltage regulator.

Figure 11 shows that when the amount of PV penetration is high, the amount of voltage fluctuation due to irradiance change becomes more significant. As shown in figure 11(c) at t=0s, all the bus are at the same voltage (0.948 p.u). However, at t=60s, when the irradiance level is low, the voltage for bus 14 settles to 0.925 p.u. for the 10% penetration case, 0.90 p.u. for the 20% case and at 0.88 p.u. for the 30% case. Figure 13 shows that similar results were obtained for case study 2.

CONCLUSION

A dynamic model of a PV generator has been developed and incorporated in a power system stability program. Using this model, it is possible to investigate the impact on the system of the fluctuating PV generation resulting from changes in irradiance caused by passing clouds. As the penetration of PV generation increases, it could have a significant effect on bus voltages. Without proper voltage control, it is unlikely that PV generation will satisfy grid regulations and this could hamper its adoption. Further research on the voltage control of PV generation is therefore needed.

REFERENCE


