THE EFFECT OF HIGH PV PENETRATION ON THE SMALL SIGNAL STABILITY OF THE POWER SYSTEM USING PSAT

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Abstract- The paper does the analysis of the small signal stability of the power system when the high PV penetration is there in the power system. The synchronous generator is displaced with the utility side PV system and the effect is observed. The eigenvalue analysis of the system is done without any PV penetration and with various levels of PV penetration and then the results are compared. The critical modes of the system are observed. The transient analysis is also done to substantiate the results obtained by the small signal stability analysis. The Power System Analysis Toolbox of MATLAB is used for the simulation.

Index Terms- Photovoltaic (PV) generation, power transmission, small signal stability, transient stability

1. INTRODUCTION

The price of the combustible fossils is increasing because of the increasing worldwide demand for the energy. These fuels also lead to problems such as solid wastes, greenhouse gas effects. So, at present the renewable energy resources which are clean energy resources are drawing more attention of the power engineers. As, photovoltaic generation is attracting growing amount of political and commercial interest the solar energy is the major option among renewable energy resources to satisfy the energy needs. For e.g. Government of India has set the ambitious target of deploying 20000 MW of grid connected solar power by 2022. According to some forecast up to 30 GW of PV penetration capacity might be installed in the U. K. by 2050. The solar energy is the clean source of the energy and it gives us the solution to the problems such as solid wastes, greenhouse gas effects. Therefore, PV generation is growing rapidly around the world. Now, connecting the PV generation to the already existing power system is going to affect the stability of the system positively or negatively. So, the study of the impact of this solar generation on the stability is important. Solar power plant consists of the solar cell and DC to AC inverters. Hence, they do not possess inertia which the traditional synchronous generators possess. In addition, their behavior and interaction with the power system depend on the dynamics of the inverter. Therefore, it is important to study the effect of the penetration of the PV on the power system dynamic performance. There are not many references available on the small signal stability of the power system considering high PV penetration. Researchers [3] and [4] discusses the impact of the PV systems connected to the utility side and rooftop PV generation connected to transmission/sub transmission system. In this paper the real power system for the simulation is used. First the modeling of the PV system is done and then it is connected to the utility side and rooftop PV to the transmission/sub transmission system. Then the PV penetration of the rooftop PV is varied while maintaining the utility side PV penetration constant. Then eigenvalue analysis is done. It is seen that as the PV penetration increases the damping ratio of the critical mode decreases. After the eigenvalue analysis the critical modes are excited in the transient analysis to validate the results obtained in the modal analysis. For the study of small signal stability considering PV system the modeling of the PV system is required. One such model is discussed in [5]. In this paper two models of the PV plant are given. One of them is detailed model and another one is the simplified version of the detailed model which is the first order model. Both models are simulated in MATLAB. The simulation results show that we can use simple model instead of detailed model without much error. Although side effects such as coupling between active and reactive power are not reproduced the proposed simple model is the good approximation of the detailed model. Then [6] discusses the modeling of solar power plant in the MATLAB. The effect of PV system on the transmission system has been the subject of the research of [9]. In this paper the conventional generator is displaced by the PV generation. Then the steady state analysis of the system is done and then transient analysis is done. The steady state analysis shows that the increasing PV penetration leads to alteration of the voltage magnitudes. In transient analysis both detrimental and beneficial impact on the power system are observed. These effects depend on the location of the fault and system topology. In this paper the WSCC 9 bus system is used for the simulation and conclusions are derived. For this PSAT is used. The eigenvalue analysis is done on the 9 bus system without PV system connecting to the system and with different PV levels connecting to the system and then results are compared to assess the small signal stability of the system. Then, the transient analysis is done to substantiate the results.
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obtained by the small signal stability analysis. This paper is organized as follows. Section II describes the concept of the small signal stability analysis. The proposed approach for this paper is discussed in section III. Section IV gives the description of the test system and the modeling of the PV system. Section V describes the analysis of the small signal stability of the system. The transient analysis is done in section VI and finally conclusions which are drawn from the analysis are given in the section VII.

II. SMALL SIGNAL STABILITY ANALYSIS

Small signal stability of the system is defined as the ability of the system to maintain the synchronism when it is subjected to the small disturbances [1]. So, there are two types instability. One is steady state increase in rotor angle due to the lack of damping torque and another one is increase in rotor oscillations due to lack of synchronizing torque. Here, the synchronous generators are replaced by the PV units consequently we are introducing the disturbance in the system. The generator turbine inertia plays important role in maintaining the synchronizing torque. So, it is important to know if a particular generator’s inertia has a significant impact on the oscillation mode.

III. PROPOSED APPROACH

For the analysis of the system the linearized model of the system is used. The system matrix A is determined and then the eigenvalues of the system are analyzed. The ith eigenvalue of the system matrix A and its corresponding eigenvectors are defined as,

\[ A\phi_i = \lambda_i \phi_i \]

\[ \psi_i^\top A = \lambda_i \psi_i \]

The eigenvalue related to the complex mode represents the frequency and damping of that mode as shown below,

\[ \lambda_i = \sigma_i + j\omega_i \]

\[ f_i = \omega_i / 2\pi \]

\[ \zeta_i = -\sigma_i / (\sigma_i^2 + \omega_i^2)^{1/2} \]

The damping ratio of the eigenvalue is related to the real part of the eigenvalue. The real part of the eigenvalue is the rate at which the amplitude of the oscillations decreases. As, eigenvalue moves to the RHP the damping of the system worsens.

The following steps are taken in the proposed approach:

1. The eigenvalue analysis of the system without any PV penetration in the system i. e. on the base case and identifying the critical modes of the system.
2. The eigenvalue analysis of the system with the various levels of the utility scale PV penetration in the system.
3. Compare the results of the eigenvalue analysis without any PV penetration and with PV penetration (i. e. comparing the results of above two points) and see the impact of the PV penetration on the small signal stability of the system.
4. Validate the results which we get from the eigenvalue analysis using transient stability analysis of the system to excite the critical modes of the system.

IV. DESCRIPTION OF TEST SYSTEM

For the analysis of the PV penetration the WSCC 9 bus test system is used. The total generation of the system is 320 MW and the total load of the system is 315 MW. There are three generators in the system as shown in the following figure (1). Three generators are equipped with IEEE type 1 governors and IEEE type 2 exciters.

In this paper we will displace the conventional synchronous generators with the utility scale PV plant. The PV generation level is varied to see the impact of the PV system on the small signal stability. The PV penetration level in the system is defined as,

\[ \text{PV Penetration} (\%) = \frac{\text{Total PV generation (MW)}}{\text{Total Generation (MW)}} \]

Now, for the solar plant the constant P and constant V solar generator is used in the PSAT. The modeling of the solar plant is given in the figure.
(2). Solar plant consists of two parts:

First one is Solar Conversion and second is DC to AC power converter. The dynamics of the solar power plant depends on this second area. Therefore, the attention must be paid to model this second area. d-q representation is used to model the DC to AC power converter. The power converter is supposed to be two independent d – axis and q – axis current sources defined by the first order transfer functions. In constant P and constant V model the value of power and voltage is defined. Then using PI controller the reference value of reactive power is generated as shown in the figure (2). Then, the reference currents id and iq are calculated using following equations,

\[ i_{d_{ref}} = \frac{P}{v_{\text{NET}}} \cdot K \]
\[ i_{q_{ref}} = -\frac{Q_{ref}}{} \cdot v_{\text{NET}} \cdot K \]

where, \( v_{\text{NET}} \) is the space vector module at the ccp point and \( K \) is the constant whose value is 3/2 for real magnitudes and 1 for the per unit magnitudes.

V. Impacts on the small signal stability of the power system

The objective of the paper is to analyze the small signal stability of the system under various levels of PV penetration. For this the critical modes of the system are identified i.e. the modes having frequency of 0.01-15 Hz and damping having less than 10% are observed. To do eigenvalue analysis the PSAT is used. First, we will analyze the system without any PV system. We will find out the critical modes of the system without connecting PV system i.e. eigenvalues of the base case. Then the critical modes of the system are observed under various PV penetration levels to check the small signal stability of the system. The critical modes of the system are as shown in the table I.

<table>
<thead>
<tr>
<th>Utility PV Penetration</th>
<th>Real Part (1/s)</th>
<th>Imag. Part (rad/sec)</th>
<th>Frequency (Hz)</th>
<th>Damping Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>-0.06882</td>
<td>1.4997</td>
<td>0.23894</td>
<td>4.584</td>
</tr>
<tr>
<td>12.5%</td>
<td>-0.08319</td>
<td>1.594</td>
<td>0.25403</td>
<td>4.626</td>
</tr>
<tr>
<td>25%</td>
<td>-0.09592</td>
<td>1.5584</td>
<td>0.24850</td>
<td>6.143</td>
</tr>
<tr>
<td>37.5%</td>
<td>-0.11716</td>
<td>1.5217</td>
<td>0.24290</td>
<td>7.676</td>
</tr>
<tr>
<td>51%</td>
<td>-0.15427</td>
<td>1.5027</td>
<td>0.24041</td>
<td>10.212</td>
</tr>
</tbody>
</table>

Table II

As, shown in the table I -6.4522+j68.6341, -6.4522-68.6341 and -0.06882+j1.4997, -0.06882+j1.4997 are the critical modes of the system. Now, the power from the PV system is penetrated at bus 7. We displace the generator at bus 2 by this PV plant. For various PV penetration levels we can see in the table II that the critical mode of the system is affected. We can observe that the damping of the critical mode is increasing. The critical mode of the system moves to the left of the complex plane. So, by displacing the conventional generator with the utility scale PV system the real part of the studied mode moves to the left hand of the complex plane.

VI. TRANSIENT ANALYSIS

The results obtained by the eigenvalue analysis are verified using transient analysis of the system. The affected critical mode of the system is excited by creating the three phase faults in the system for various PV penetration levels.

<table>
<thead>
<tr>
<th>Participation Factor</th>
<th>Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0097</td>
<td>Bus 3</td>
</tr>
<tr>
<td>0.1015</td>
<td>Bus 2</td>
</tr>
<tr>
<td>0.1061</td>
<td>Bus 1</td>
</tr>
</tbody>
</table>

Table III

Participation Factors of the machines participating in the critical mode -0.06882+j1.4997 affected by the PV penetration

The table III shows the participation factors of the various generators participating in the critical mode of the system. From the table III we can see that the machine at the bus 1 participate more in the critical mode. So, to excite this mode we create three phase fault at bus 1. This fault is cleared in one cycle. The speed of the generator at bus 1 is shown in the figure (3), (4) and (5) for different levels of PV penetration.
From the figures (3), (4) and (5) we can see that the oscillations in the speed of the generator at bus 1 is decreasing as we increase the PV penetration in the system. We see that the oscillations are more in the base case and they are decreased when PV penetration is 51%. Similarly the real power of the generator 1 is shown for the same three cases in figures (6), (7) and (8) and we find that the oscillations are decreasing as we increase the level of the PV penetration.

CONCLUSION

In this paper, the impact of the PV system on the power system is investigated. The WSCC 9 bus test system is used for the analysis. First, the eigenvalue analysis is done on the base case and then the eigenvalue analysis is done for the various levels of the PV penetration. For the small-signal stability analysis first the critical modes of the system are identified and then it is observed where these studied modes are moving in the complex plane and then results of this analysis are substantiated by the transient analysis. It is observed that as we displace the conventional generator by the PV system the eigenvalue moves to the left hand of the complex plane which means that the system becomes more and more stable. The inertia of the system is reduced as we displace the conventional generators by utility scale PV plant. So, we conclude that as the inertia of the system is reduced the critical mode of the system is impacted beneficially which means that the stability of the system is improved by displacing conventional generator by utility scale PV plant. The results obtained by the eigenvalue analysis is substantiated by the transient analysis. For this first participation factor of the critical mode is calculated. Participation mode shows which generator bus participates most in that mode. So, we create three phase fault at that bus to excite that particular mode. Then, the oscillations in the speed and real power of the three generators are observed. It is seen that the oscillations in the speed and real power are decreasing as the PV penetration is increasing and oscillations are less when PV penetration is 51%. So, the results which are obtained from eigenvalue analysis are validated using transient analysis.
REFERENCES