Investigation of Impacts of Solar PV on Transmission System Voltage Stability Considering Load Characteristics and Protection

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Content

- Motivation and aims
- Study approach
- Modeling of the system
- Case studies: Results
- Conclusions
Motivation: Why this study

- Growing number of solar PV projects worldwide

- Intermittency/uncertainty of power production from solar PV

- Effect of location of solar PV on the stability of the system:
  - Large scale PV farms installed at areas with high irradiance levels which tend to be far away from load centers

- Needs of studies on impacts of large scale solar PV on voltage stability considering:
  - Changes in solar Irradiance
  - Protection system and load characteristics.

Source: IEA, "Renewables 2017"
Aims

• Investigate impacts of large-scale solar PV on the voltage stability of transmission system, considering:
  ✓ load characteristics
  ✓ location of solar farm
  ✓ variation of solar irradiance.
  ✓ distance protection of transmission system
Study approach

• Step-1: Determine best placement of solar PV in the Nordic-32 test system based on solar irradiance
• Step-2: Determine maximum penetration of solar PV in the system, considering frequency requirement
• Step-3: Carry out voltage stability analysis:
  ✓ Study of post-disturbance voltage recovery time analysis with high solar PV penetration with fixed solar irradiance
    ○ Role of the protection system
  ✓ Voltage stability analysis considering changes in solar irradiance and load profile
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- **Modeling of the system**
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Placement of solar PV in Nordic-32 test system

- The highest solar irradiance is found in the eastern part of the network.
  - Install PV farms in east side of the grid

Solar irradiance distribution in Europe

Modified Nordic-32 test system (green buses represent solar PVs)
Characteristics of Nordic-32 test system

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Number of Buses</td>
<td>41</td>
</tr>
<tr>
<td>Total Generation</td>
<td>11558 MVA</td>
</tr>
<tr>
<td>Peak Solar Generation</td>
<td>≈ 3700 MVA</td>
</tr>
<tr>
<td>(in June) with 30%</td>
<td></td>
</tr>
<tr>
<td>penetration</td>
<td></td>
</tr>
<tr>
<td>Total Load</td>
<td>11443 MVA</td>
</tr>
<tr>
<td>Fixed Shunt Compensation</td>
<td>1375 MVAr</td>
</tr>
</tbody>
</table>

- The system also consists of induction motor loads.
- Most of the loads are concentrated in the southern part.
- Solar PVs are installed on the eastern side of the network.

Modified Nordic-32 test system (green buses represent solar PVs)
Characteristics of Nordic-32 test system

- Dynamic analysis of the system is performed using PSS/E.
- All components modelled using built-in PSS/E dynamic models:
  - Solar PV plant and its voltage source converters
  - Turbine governors and over-excitation limiters
  - On-load tap changers.
  - Induction motor loads, constant current loads and constant impedance loads.
  - Three-zone distance relays for transmission line protection
Maximum Penetration of solar PV

Max penetration level should limit the max frequency deviation by 0.5 Hz in case of a contingency.

Frequency with different PV penetration levels after sudden loss of large generation unit.

30% PV penetration slightly exceeds by the 0.5 Hz threshold but has been selected for this study.

Penetration % = \frac{\text{PV production}}{\text{Total active generation of base case}}
Simulated solar PV plants

A solar PV model in PSS/E

<table>
<thead>
<tr>
<th>Single PV plant rating</th>
<th>600 MW ± 200 MVar</th>
</tr>
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<tbody>
<tr>
<td>Irradiance levels</td>
<td></td>
</tr>
<tr>
<td>600 W/m² yields 100% of the rated power</td>
<td></td>
</tr>
<tr>
<td>400 W/m² yields 95% of the rated power</td>
<td></td>
</tr>
<tr>
<td>200 W/m² yields 50% of the rated power</td>
<td></td>
</tr>
<tr>
<td>Controller</td>
<td>P-V control mode</td>
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</table>
Setting of distance relays

• Zone 1: covers 80% of the protected line with a time delay of 5 cycles
• Zone 2: covers 100% of the protected line and 20% of the shortest adjacent line with a time delay of 15 cycles
• Zone 3: covers 100% of the protected line and 120% of the shortest adjacent line with a time delay of 30 cycles
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Study cases

- Post-disturbance voltage recovery time analysis with solar PVs producing at their rated power
- Voltage collapse analysis while considering changes in the solar irradiance and the load profile
Post-disturbance voltage recovery

Impacts of solar PV:
Solar PVs contribute to delayed voltage recovery time
- Steady state voltage is lower
- Installed far away from the load center
- High reactive power losses on the network

Impacts of induction motors:
Induction motors tend to worsen voltage recovery times due to their fast power restoration dynamics
Simulated faults

Post-disturbance voltage recovery

Trip due to overloading after the second fault

Voltage collapse may occur after these lines are cascaded and tripped.
**Post-disturbance voltage recovery**

**Impacts of solar PV:**
- Voltage collapse occurs in case with 30% PV

**Impacts of protection:**
- Cascade trippings of zone-3 relays on 4032-4042, 4041-4044 and 4041-4061
  - PV plants are located in the east of the network and thermal plants which are close to the load center were shut down.
  - Large power flows through the critical transmission lines from north to south
Changes in solar irradiance and load profile

- Consider 4 seasons
- Load profile during each of those periods closely mimics the load profile of the Nordic power system.
- Irradiance profiles for the regions are used to calculate power generated by the PVs.

The average power generated by the solar PVs
Changes in solar irradiance and load profile

Simulations performed for three cases:

<table>
<thead>
<tr>
<th>Case</th>
<th>Solar</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HIGH (95% PV rated power)</td>
<td>HIGH</td>
</tr>
<tr>
<td>2</td>
<td>HIGH</td>
<td>LOW</td>
</tr>
<tr>
<td>3</td>
<td>LOW (ZERO)</td>
<td>VERY HIGH</td>
</tr>
</tbody>
</table>

Simulation steps in each case:

- The simulation will be run for 550 s. Every 50 s the irradiance value will change.
- Faults applied on the critical transmission lines in sequence:
  - 4032-4044 at T = 100 s
  - 4042-4044 at T = 200 s
  - 4031-4041 at T = 300 s
  - 4042-4043 at T = 400 s
Case 1: High solar high load

Voltage collapse occurred for June, September after the first fault.

The system was more prone to voltage instability due to:

- High PV production during the month of June and September (when the Irradiance is very high)
- Most conventional generations close
Case 2: High solar and low demand

Voltage collapse has occurred after the fourth line fault ($T = 400$ seconds) in all seasons except in June.

In June at 6 a.m. the load profile is lowest compared to the rest of the months while the irradiance is highest.
Case-3: Low solar and high demand

Voltage collapses occurred after 3rd and 4th faults.

More solar, more prone to voltage instability when comparing Case 1 and Case 3.
- Solar irradiance has been reduced almost to zero.
- PV plants still provide reactive power support.
Conclusions

High PV production tends to contribute to delayed post-disturbance voltage recovery time. Induction motor loads further worsened the voltage recovery time. Zone-3 relays can further cause cascading tripping of lines.

Voltage stability gets worsen during periods of high PV production due to significant reactive power losses in the transmission lines and lower production from conventional generations.

Voltage stability gets improved during periods of low solar irradiance due to reactive supports from PV plants.

The conclusions are however dependent on:
• Characteristics of networks
• Locations of PV plants
• Control modes of PV plants
Post-disturbance voltage recovery

**Impacts of solar PV:**
Solar PVs contribute to delayed voltage recovery time

- Steady state voltage is lower
- Installed far away from the load center
- High reactive power losses on the network